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ANALYSIS AND MOVING BASE SIMULATION OF TRANSITION CONFIGURATION MANAGEMENT ASPECTS OF A POWERED LIFT AIRCRAFT

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FOREWORD

The research reported here was sponsored by the Ames Research Center, National Aeronautics and Space Administration. It was conducted by Systems Technology, Inc., Hawthorne, California, under Contract No. NAS2-6441 with NASA support for the simulation experiments. The NASA Project Monitors were James A. Franklin and Everett A. Palmer.

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SYMBOLS

a_x	Total longitudinal acceleration
D	Drag
f_1, f_2, f_3	Functions
g	Acceleration due to gravity
h	Altitude
IAS	Indicated air speed
K_1	Gain
M_{δ_e}	Elevator control power stability derivative
n_z	Normal load factor, g's
q	Pitch rate
$\bar{q}$	Dynamic pressure
RCAH	Rate command attitude hold
s	Laplace operator
SAS	Stability augmentation system
T	Thrust
T_{L_u}	Time constant
V	Airspeed
$\bar{V}$	Smoothed airspeed
W	Aircraft weight
X	Longitudinal coordinate
Z_{δ_F}	Flap control power stability derivative
α	Angle of attack
γ	Flight path angle

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δ_c	Longitudinal column deflection
δ_e	Elevator deflection angle
δ_F	Flap deflection angle
δ_T	Throttle deflection angle
δ_ν	Nozzle deflection angle (0 deg is aft and 90 deg is down)
$\Delta(\ )$	Increment in ( )
θ	Pitch attitude
$(\dot{\ })$	d( )/dt

<u>**Subscripts**</u>

c	Command (except for δ_c)
GS	Glide slope
o	Nominal value
ϵ	Error

SECTION I

INTRODUCTION

A. GENERAL

This is the second in a series of reports documenting analytical and moving-base simulation results of a study to improve flight safety and operations of the Augmentor Wing Jet STOL Research Aircraft. Such improvements were to encompass both flight control system (FCS) and flight director (FD) aspects; and, initially, were to reflect little, if any, of the practical (cost-associated) hardware considerations imposed on the full-scale aircraft itself. As the study progressed, this open policy gradually tightened in view of the favorable results and the desirability of implementing certain of the concepts on the actual airplane.

Many of the detailed study results, while important to the development of overall perspective and specific insight, are considered quite "routine". Similar findings (e. g., relating to piloting technique, inner-loop stability augmentation systems, etc) are already reported in the literature (e.g., Refs. 3-7). Accordingly, such aspects of the study are but mentioned (and referenced) in passing; and the report concentrates, rather, on only the more significant and novel aspects of the work accomplished.

Among the latter, a most important result has been the concept and implementation of a configuration management FCS designed to take the guesswork out of, and improve the operational safety of, transition flight in the region from cruise to STOL. This is the subject of the present report. Other reports (Refs. 1 and 2) cover those study phases devoted to improved flight directors and to the application of both FCS improvements and flight directors suitable for use in STOL approaches involving decelerating, descending, curved paths.

B. SPECIFIC

At the time the project was initiated, there was relatively little experience with detailed flight control problems and procedures for the Augmentor Wing aircraft. It was being flown on the Ames Research Center Flight Simulator

for Advanced Aircraft (FSAA) in a "first-flight" configuration embodying the best available aerodynamic data and a minimum (funds-limited) contractor-designed stability augmentation system (SAS). The approach configuration had been set to permit one-engine control and abort; and project pilots, flying 7-1/2 deg approaches in the absence of winds and shears, had developed suitable control techniques. However, the airplane was considered unforgiving, even when on the acquired glide slope. Furthermore, the level-flight (constant altitude) transition process from 120 to 60 kt consisted of essentially a one-step maneuver which involved: setting thrust to that required on the glide slope; using the nozzle to rapidly decelerate; and deflecting flaps in rough accordance with its placard speeds. There was no real appreciation for control, or available margins, about any of the resulting transitory flight conditions during the transition. Clearly, it was advisable and necessary to investigate and develop potential improvements in the trim configuration management aspects of the transition process; not only for operational safety in the experimental program, but also as would eventually be required for civil transports. This development and the results obtained are the subject of the present report.

SECTION II

ANALYSIS

The Augmentor Wing aircraft has, in common with many powered STOL or VTOL aircraft, a redundant set of basic longitudinal controls; i.e., elevator, flaps, throttle, and thrust vector angle.* This redundancy permits the aircraft to be trimmed for a given steady speed, angle of climb, and attitude in any one of a large number of control combinations as depicted generically in the Fig. 1 sketch. (Trim elevator angles, not shown, are of course related to the angle of attack which is a more pertinent control parameter.) The bounds on this figure are either physical limits (e.g., max or min δ_T, δ_ν, or speed-associated flap placards) or represent areas where flight safety or comfort is deficient (e.g., stall α, min θ). For other aircraft, additional limits due to buffet, deficient handling, etc., might be superposed. Qualitatively similar (but quantitatively different) plots for each speed and path angle make up the totality of the trim space available. [Note that a given steady path angle is equivalent also to an instantaneous acceleration and a different path angle in accordance with the general trim condition: $(T-D)/W \doteq \gamma + \dot{a}_X/g = \text{constant}$.]

A. TRIM "CORRIDOR" CONSIDERATIONS

The wide range of possible trim conditions inherent in the above picture seems to be highly desirable from the standpoint of enhanced operational flexibility. However, considering the available incremental performance, safety and comfort margins, handling characteristics, etc. about a given trim condition, much of the total available steady trim space is not safely nor comfortably usable. A completely flexible approach to trim management can therefore result, at worst, in inadvertent, dangerously marginal conditions; or, at best, in near-optimum, safe, high-margin conditions. To insure that the best possible trim conditions are always used, and to prevent inadvertent incursions into marginal regions, it is advisable to narrow the trim space to a "desirable" corridor. This concept is depicted schematically in Fig. 2.

*Thrust vectoring is accomplished via Pegasus nozzles that can rotate the exhaust throughout the range of 6 deg (nozzles essentially aft) to 104 deg (nozzles down, and slightly forward).

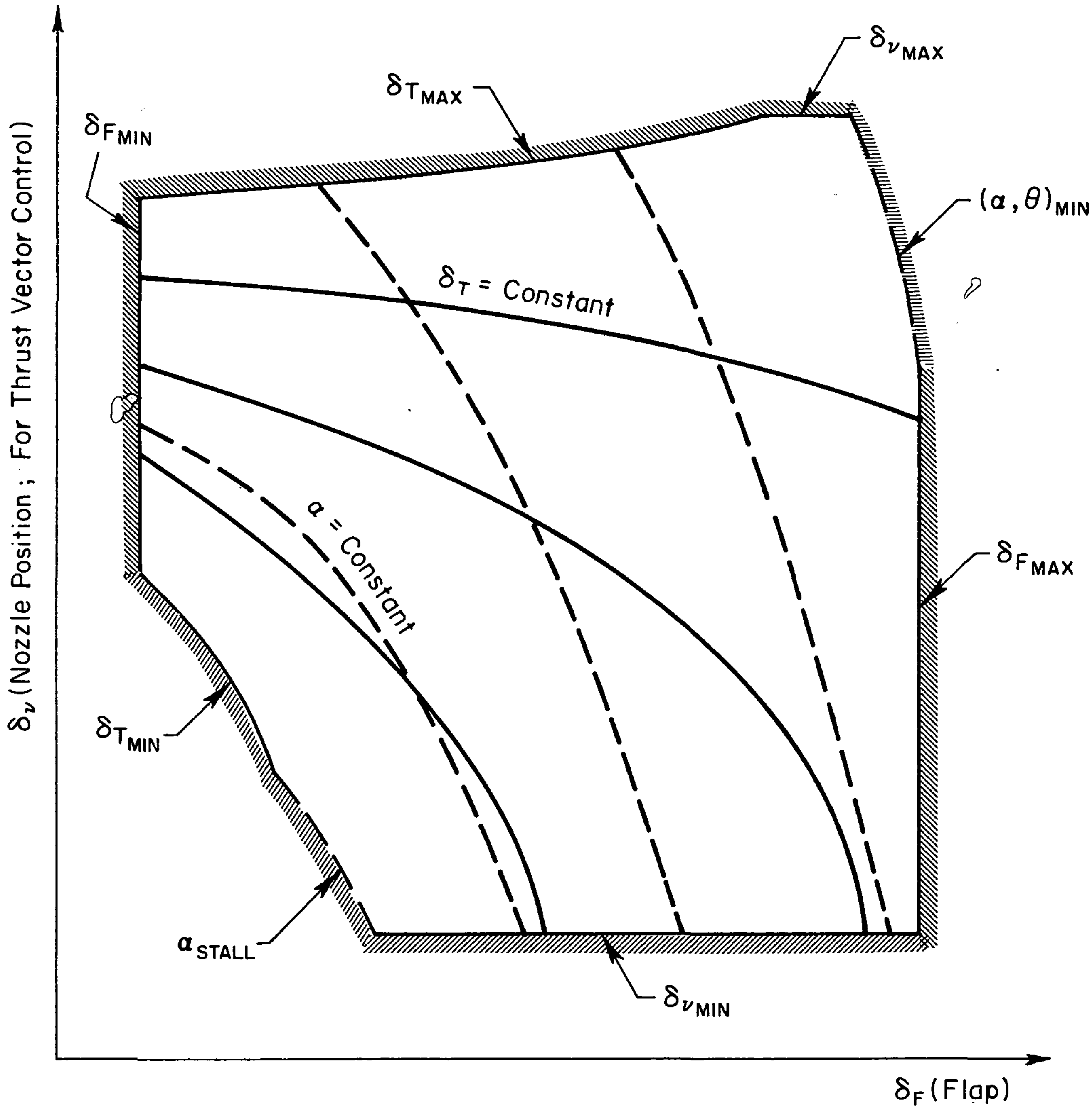


Figure 1. Generic Plot of Operational Window for Constant Speed and Flight Path Angle (or a_x)

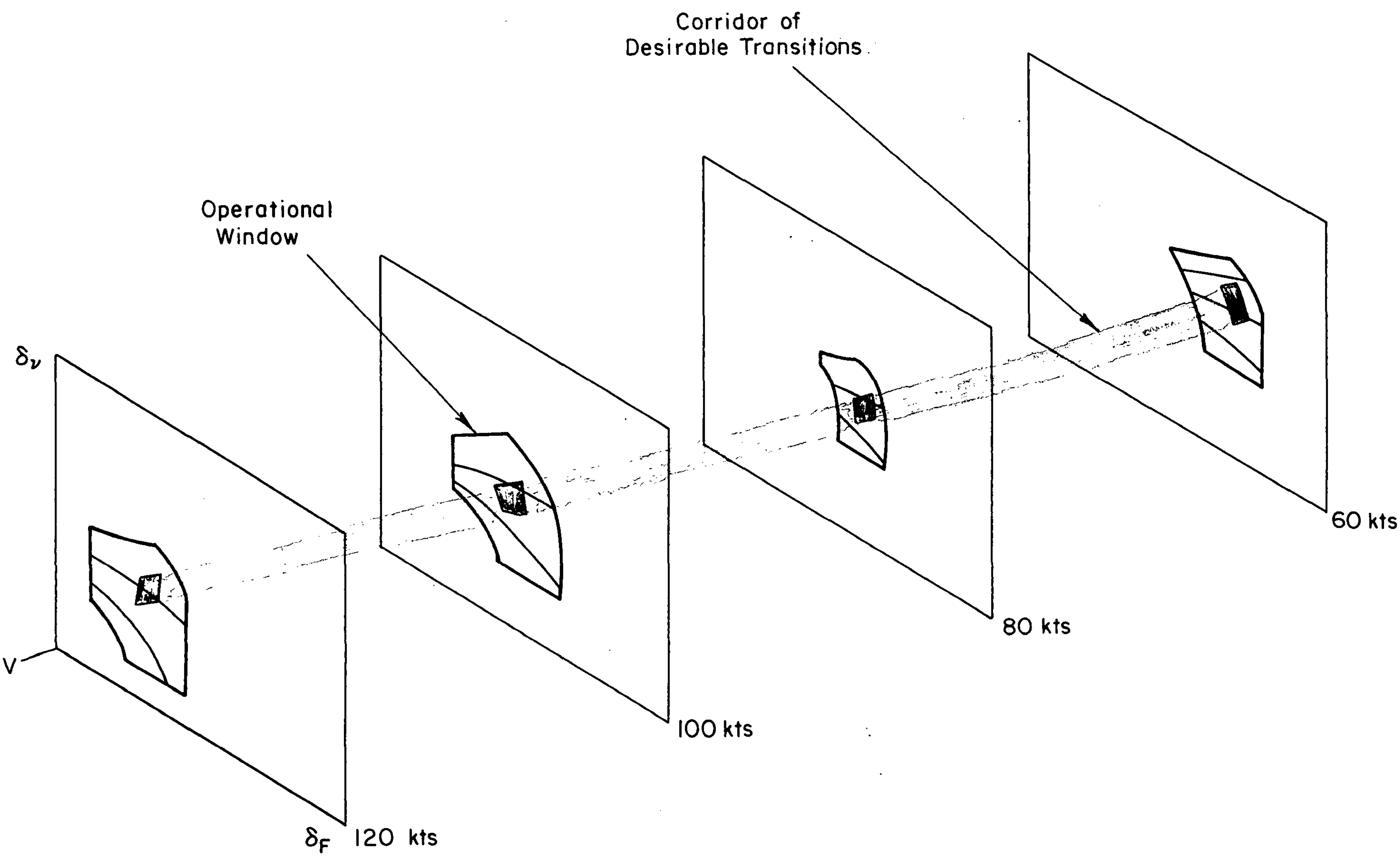


Figure 2. Generic View of Available and Desirable Trim States

To implement this concept requires that the chosen corridor have the best obtainable characteristics relative to the following desirable properties for the transition "manuever".

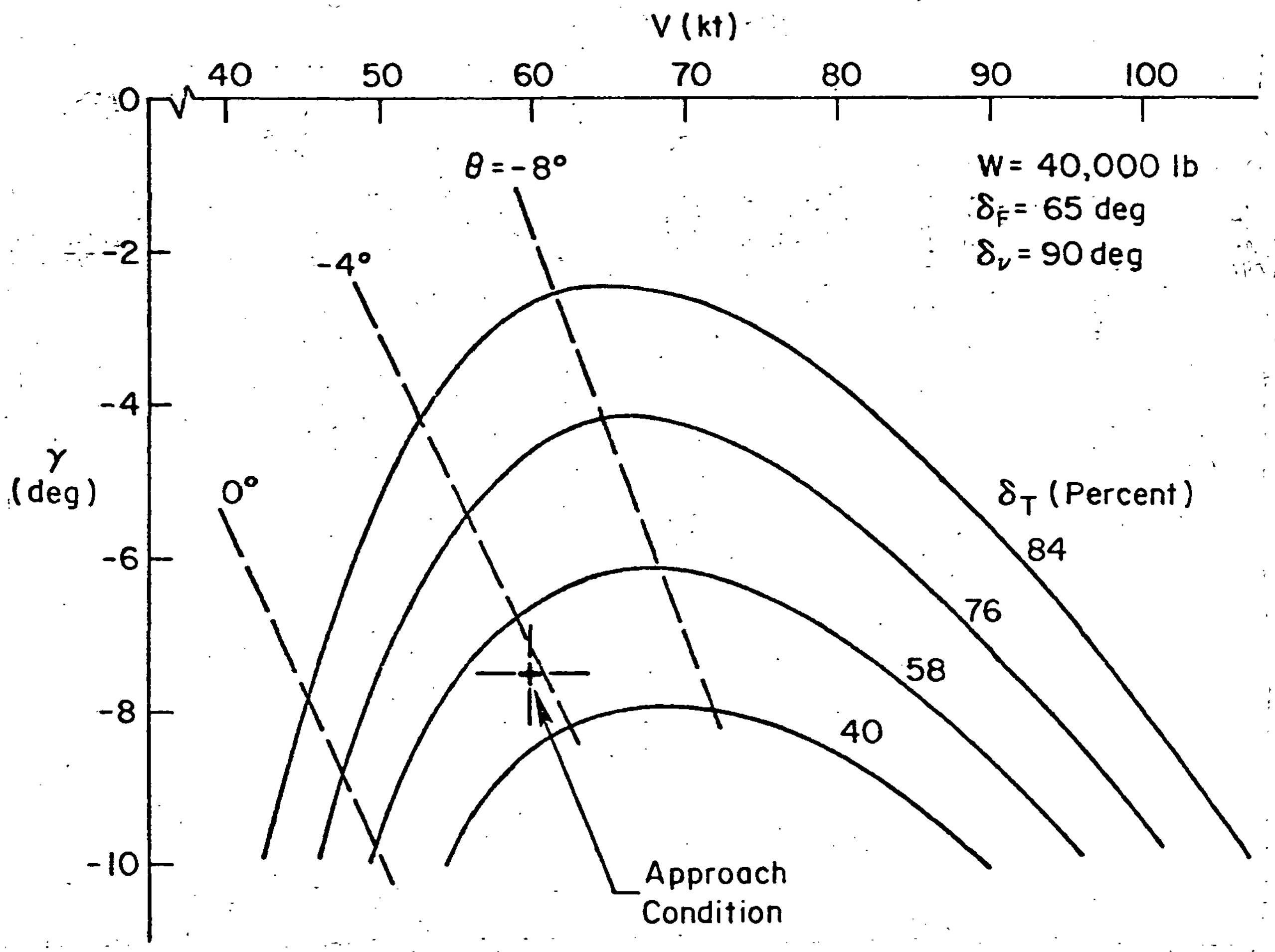
1. Adequate closed loop small perturbation control about all trim operating points with a uniform piloting technique: to permit positive control of progression (or regression) through the transition trim states.

2. Adequate $\pm\Delta\gamma$ (or Δa_x) control

3. Only small changes in trim attitude and angle of attack (the first to ease the piloting-workload problem, and the second to preserve stall margin)

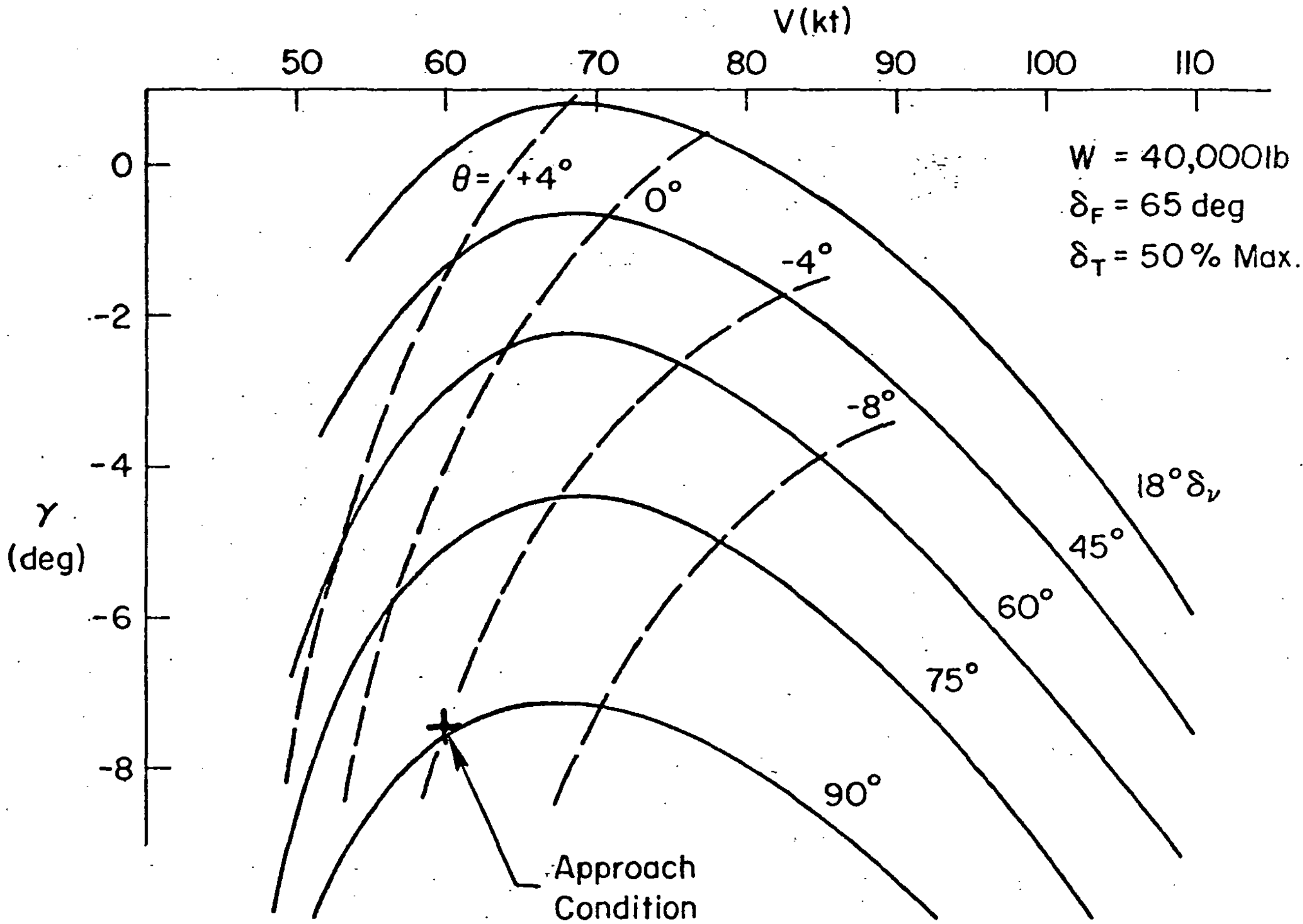
4. Monotonic trim configuration settings as a function of speed

The first point requires some initial consideration of the most desirable piloted control technique, i.e., how γ and V changes (about given operating points) are to be effected. In this connection, early closed-loop studies showed that controlling $\dot{h}$ or γ with the nozzle (rather than with throttle), and V with attitude (through elevator) was the best control strategy. This choice can be appreciated by reference also to the performance plots of Fig. 3 (see also Ref. 3). These plots show directly the steady state responses to two alternative sets of primary means of control: pitch attitude changes by means of the elevator, and either power (Fig. 3a) or nozzle (Fig. 3b) inputs. Figure 3a shows that, when trimmed for approach (symbol +), throttle (power) changes at constant pitch angle produce an adverse coupling. That is, thrust (and γ) increases are accompanied by <u>decreases</u> in airspeed. Pitch attitude inputs at constant power result in direct and proper airspeed change but with a "reversed" flight path change in that raising the nose causes an increased steady rate of descent (because the airplane is trimmed on the backside of the drag curve). Therefore, using attitude to control airspeed and throttle to control path angle (as for usual backside conditions) will in this case require the pilot to nose over with added power, a highly unconventional and hazardous technique when approaching the ground. If attitude is held and throttle increased, there will be a large initial flight path response (overshoot) which then decays as speed bleeds off. Because of such difficulties, pilot opinion of flight path control will be less than satisfactory. (The particular technique corresponding to Fig. 3a was rated in Ref. 4 as 3-1/2–5 for VFR approaches with no turbulence.)



a) Throttle Inputs (Taken from Ref. 4)

Figure 3. Performance Curves for Augmentor Wing Aircraft



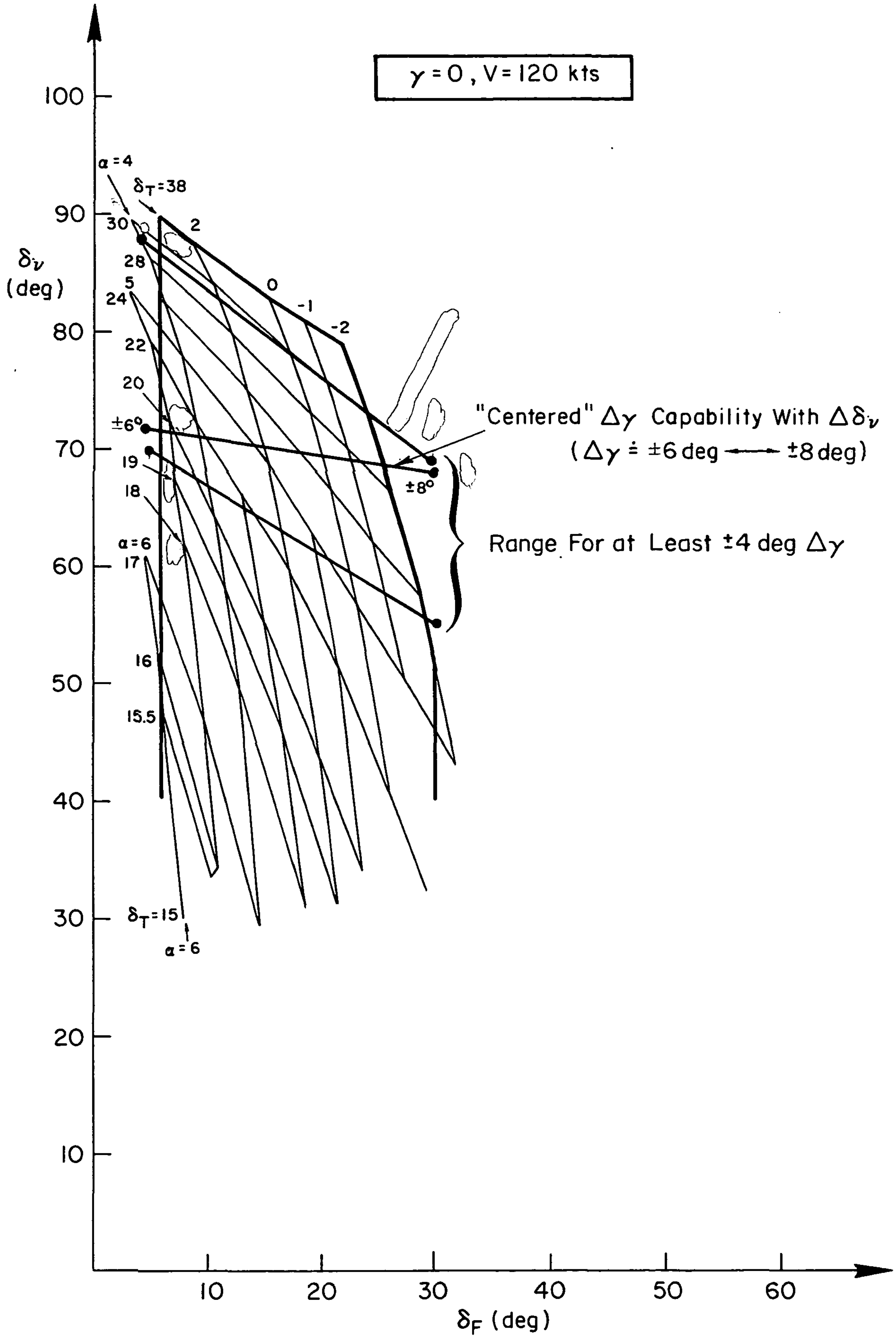
b) Nozzle Inputs (Adapted from Ref. 4)

Figure 3 (Concluded)

If nozzle deflection (rather than throttle) is used to control flight path, Fig. 3b shows that the resulting speed responses at constant attitude are favorable, i.e., the flight path responses will not display the overshoot tendencies accruing to throttle inputs. The Ref. 4 pilot rating for flying the approach with nozzle control (corresponding to Fig. 3b) was 3. References 5 and 6 present generalized results pertaining to the subject of airspeed, flight path "coupling" and path response "overshoots" which lend further detailed support to the above arguments.

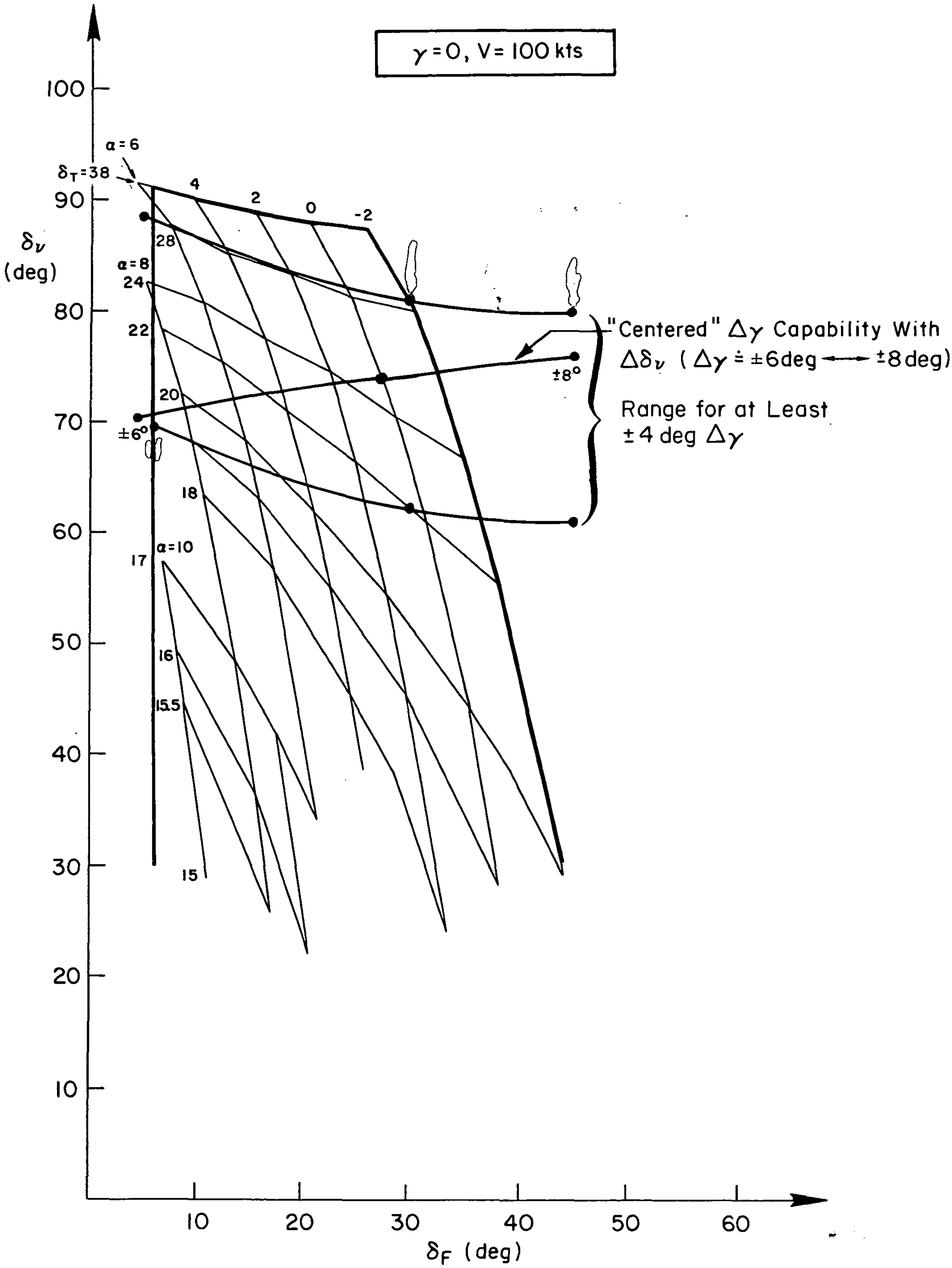
The upshot of the foregoing is that, for the basic aircraft (no SAS), manual control of γ with nozzle rather than throttle is the desirable strategy. It is important, therefore, in constraining the trim conditions to select regions in the available control space which reflect good nozzle control of γ. Accordingly, we seek a transition trim corridor where the "Items 1 and 2" requirements in the above listing are met primarily by use of the nozzle, and throttle usage is minimized (both to avoid undesirable speed bleedoff and to simplify the piloting task).

In view of the above, a first step in the definition of the most suitable trim conditions was to establish the vehicle configurations giving near maximum $\pm\Delta\gamma$ control with the nozzle. These configurations are represented by a region that cuts across the complete trim envelopes as shown in Fig. 4. (Figure 4 is based on computed "data" supplied by ARC. Any discontinuities in the plots are due to the computer generation scheme.) Within this already restricted region we can impose further restrictions to confine the α range to safe, comfortable and easily controlled limits; and further to consider possible restrictions on throttle setting requirements. Notice that in general the good $\Delta\gamma$ region corresponds to trim conditions involving large nozzle trim settings (roughly 60° to 90°). This is consistent with the desired generation of thrust to increase both climb rate and airspeed as in Fig. 3b. That is, nozzle deflections about these large settings produce primarily forces in the X direction (Δ thrust rather than Δ lift changes). Accordingly, the restricted region provides not only excellent nozzle control-power ($\pm\Delta\gamma$) for off-nominal conditions (e.g., head wind and tail wind shears) but also offers good incremental nozzle characteristics for closed-loop control.

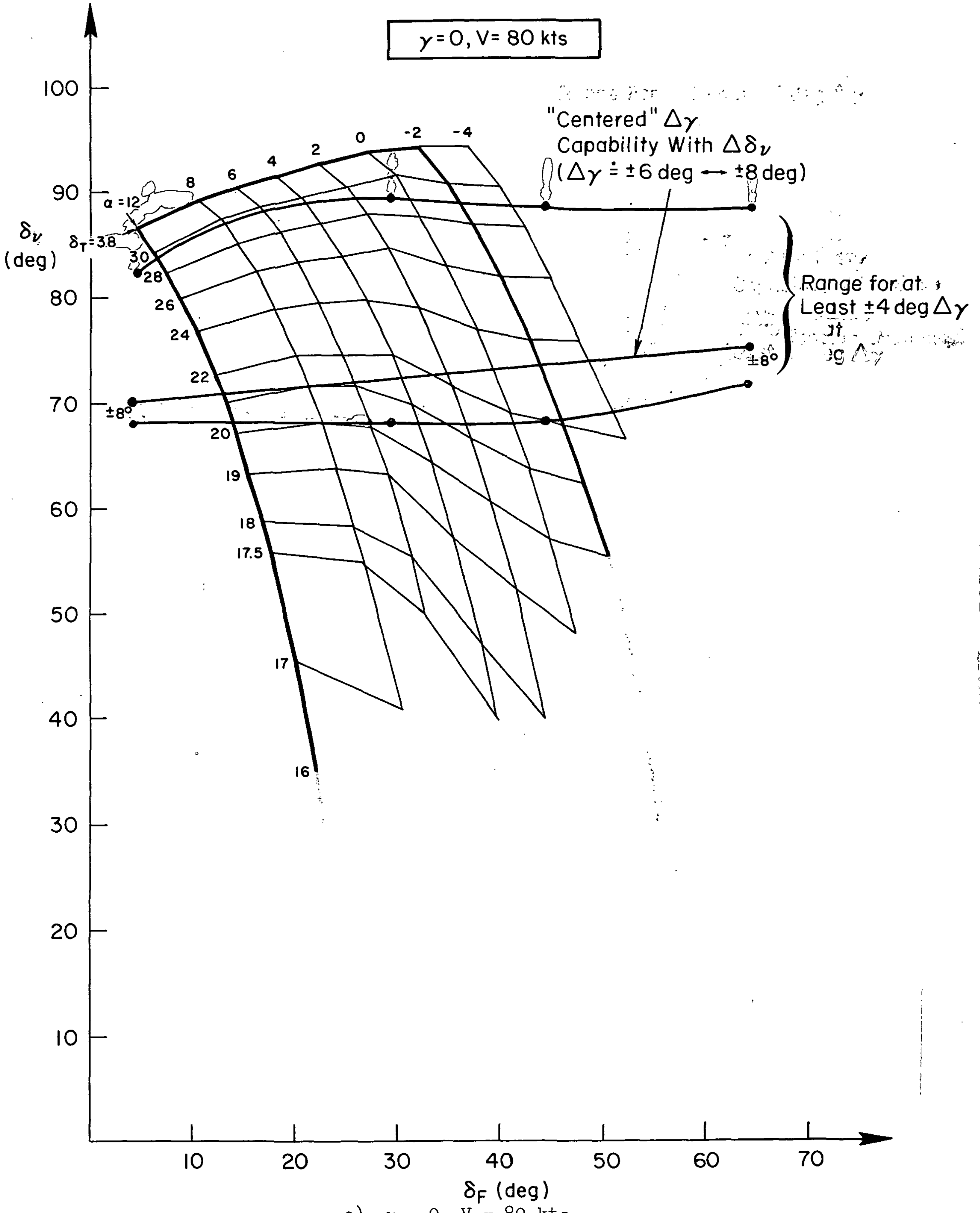


a) γ = 0, V = 120 kts

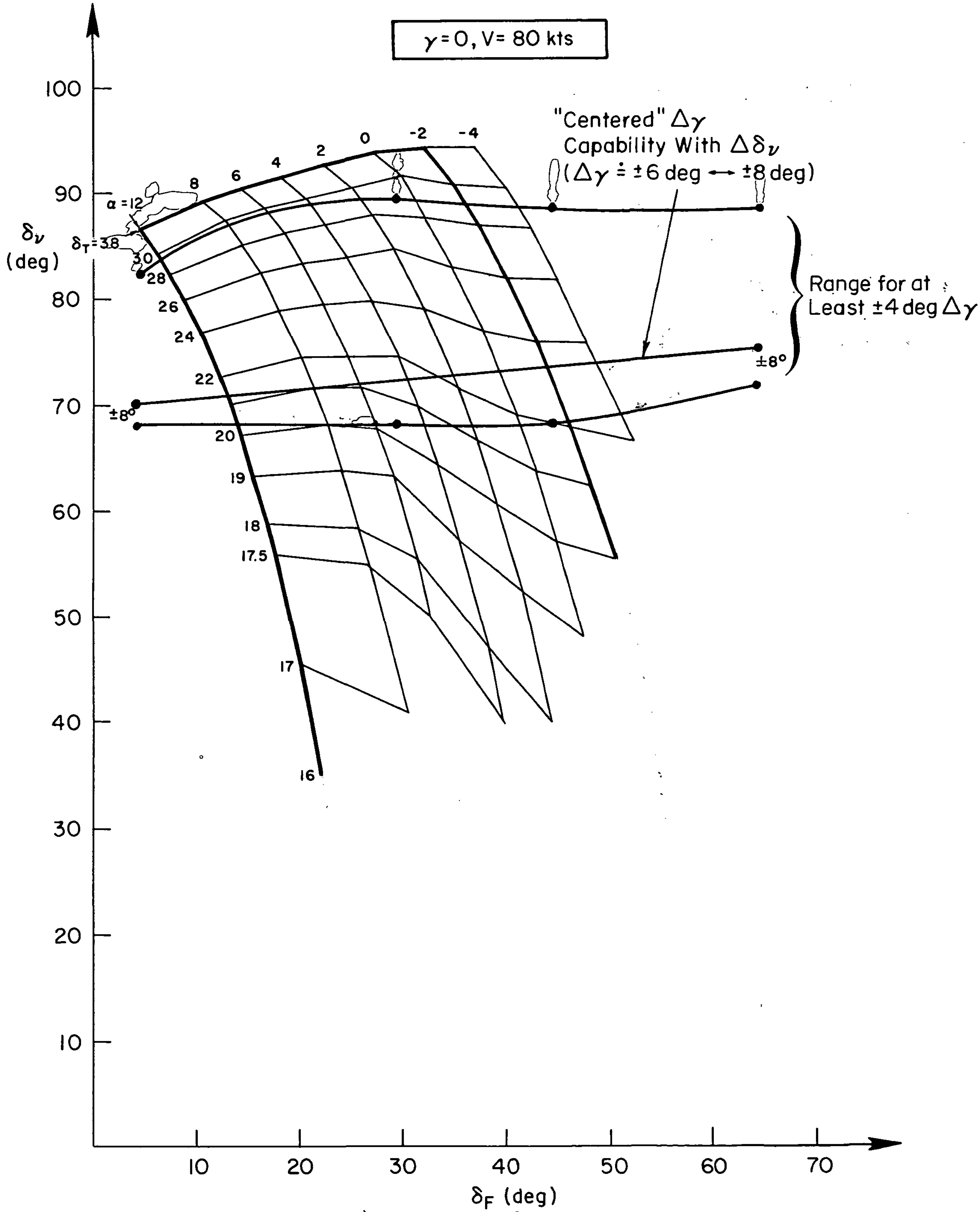
Figure 4. Nozzle vs. Flap Trim Curves for Augmentor Wing Aircraft



b) $\gamma = 0$, V = 100 kts
Figure 4 (Continued)

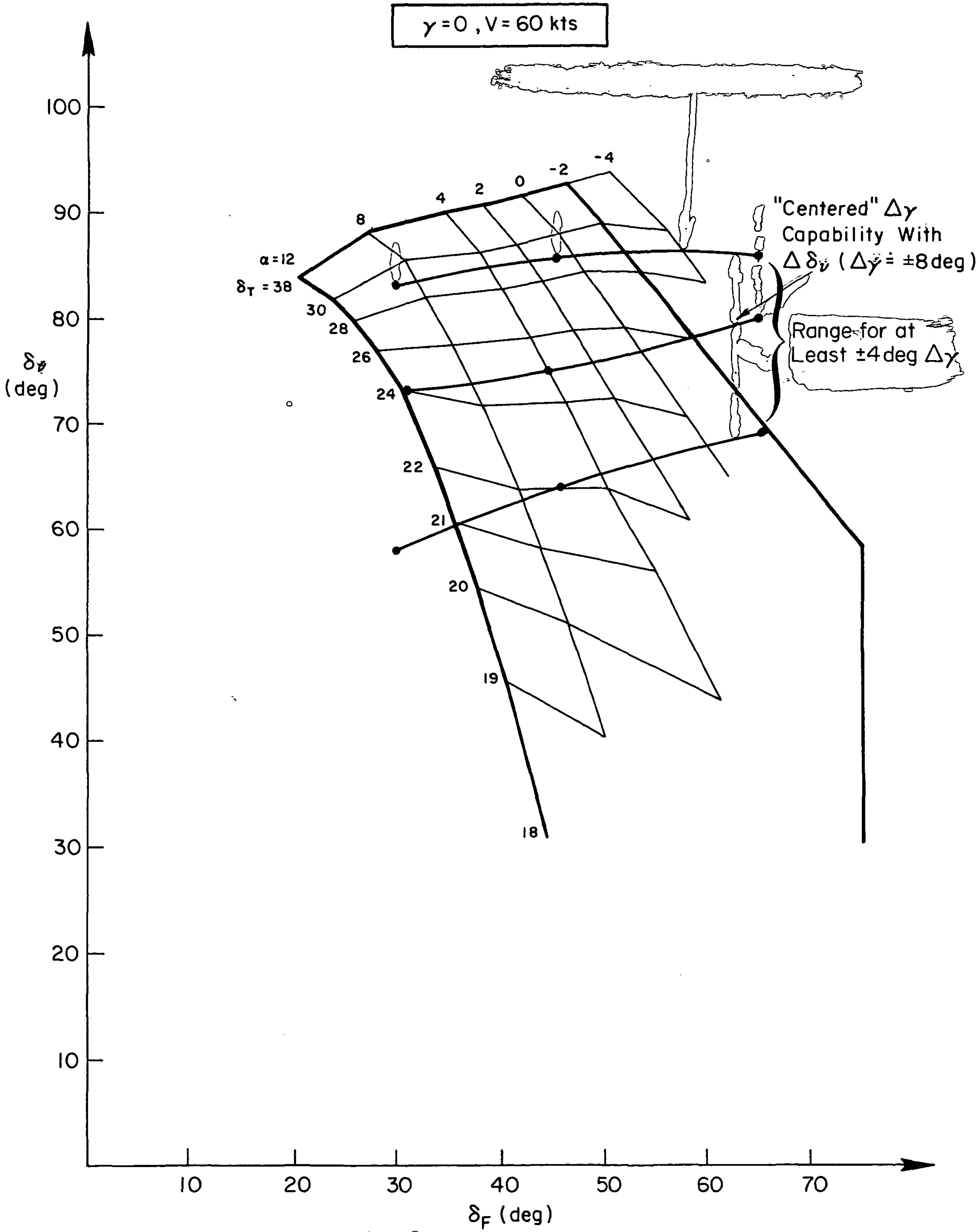


c) $\gamma = 0$, V = 80 kts
Figure 4 (Continued)



c) $\gamma = 0$, V = 80 kts

Figure 4 (Continued)



d) $\gamma \doteq 0$, V = 60 kts

Figure 4 (Concluded)

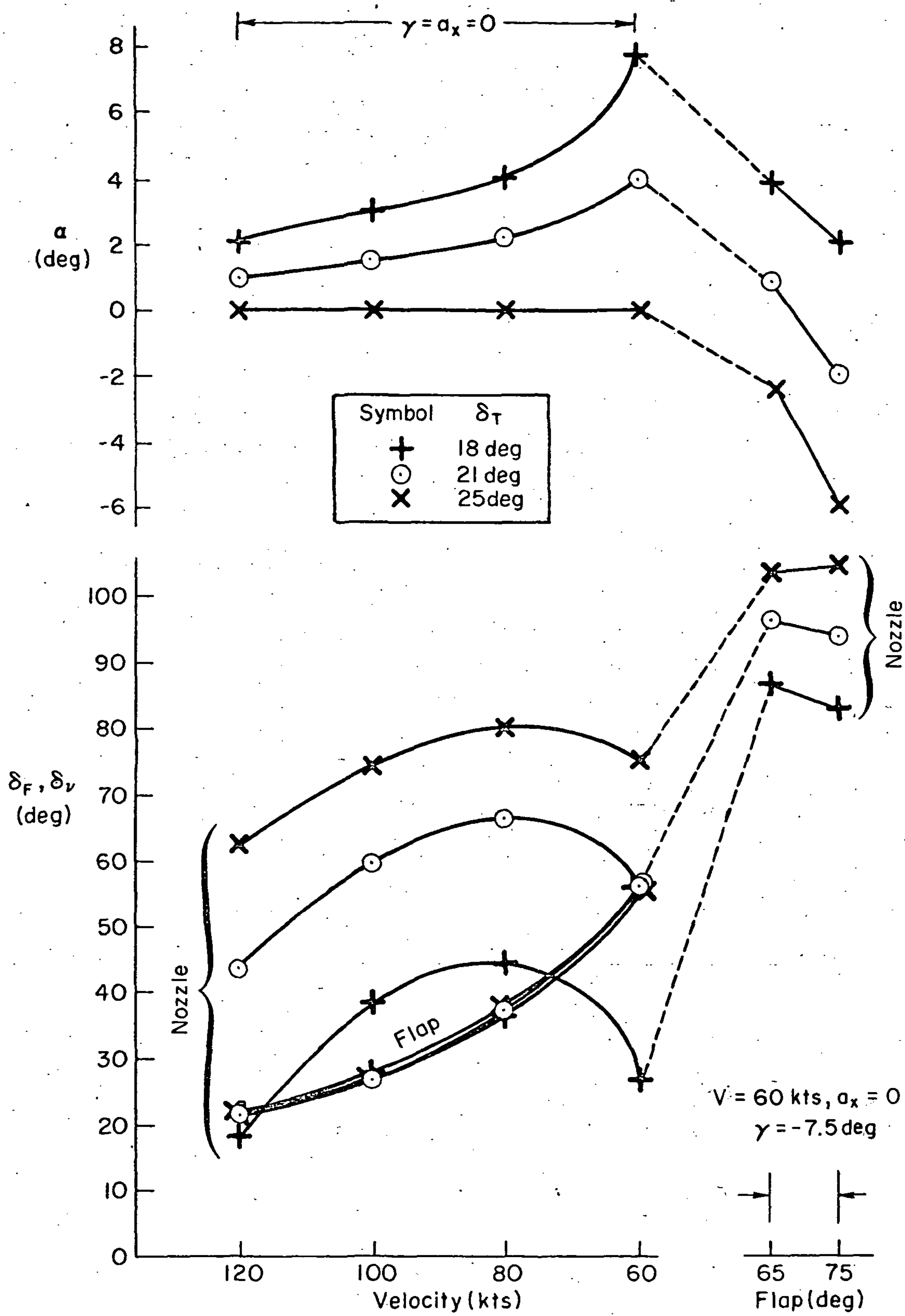


Figure 5. Range of Desirable, Constant Throttle, Trim Conditions for Transition

Within the restricted region we can now ascertain the steady trim conditions for a range of constant throttle settings (desired for easy piloted control) as in Fig. 5. We see here that $\delta_T = 25^\circ$ represents a very simple and safe schedule in that α is constant and small ($\doteq 0$) throughout level-flight ($\gamma = 0^\circ$) transition; furthermore, the available climb capability is near-maximum (i.e., $\delta_T = 25^\circ$, $\alpha = 0$ is in the center of the good climb band in Fig. 4) for speeds less than 120 kt. The lower throttle settings shown require increasing α as speed decreases, and incur a reduced climb capability (compared with $\delta_T = 25^\circ$). However, from the standpoint of reduced fuel consumption and noise (not a restriction seriously considered in this first phase exploration, although influencing later phases of the total program — Ref. 2), the lower settings are desirable. Also, they are more compatible with avoiding nozzle saturation on the $\gamma = -7.5^\circ$ glide slope. For example, at high power, the nozzle settings approach the maximum forward limit ($= 104^\circ$); therefore, descent capability with nozzles (only) is severely restricted. Reducing power reduces nozzle trim and thereby increases the available deflection about trim. The resulting improved descent capability is further enhanced by increased flap deflection (from 65° to 75°). This is not true for the high power setting where increasing flap deflection has little effect on the trim nozzle setting and produces uncomfortable pitch attitudes. For example, for $\delta_F = 75^\circ$, $\delta_T = 25^\circ$ the angle of attack is about -6°, and the resulting nose down attitude is therefore about 14°.

On the basis of the foregoing considerations, the trim schedule tentatively adopted for further exploration and simulation is that corresponding to $\delta_T = 21^\circ$.

B. POSSIBILITIES FOR IMPROVED TRIM MANAGEMENT AND CONTROL

Using such a "nominal" schedule as the basic building block, it appears that improved operational control and trim management can be achieved by successive levels of automation as follows.

1. Manual Control

The obvious feature of the trim schedule rendering improved control possible (either manually or by increasingly automatic means) is the observed direct relation between speed and flap position. By adhering to this flap schedule

(say in stepwise increments or "detents") the pilot can now achieve controlled transition while maintaining good flight characteristics. Notice (Fig. 5) that with this flap schedule the general nature of the corresponding nozzle deflection with speed is the same over the probable range of throttle settings. Therefore, throttle changes from "nominal" can be offset by simply adding a nozzle bias to the basic nozzle-flap relationship (e.g., Fig. 6). Similarly, nozzle biases can be offset by constant throttle increments. Without such counteracting offsets, auxiliary calculations show that nozzle or throttle biases on a given (Fig. 5) trim combination result in roughly uniform increments in climb/descent or acceleration/deceleration over the entire transition speed range. That is, a nozzle increment of 15°, roughly equivalent to a throttle decrement of 3°, produces about $\Delta\gamma = -3^{\circ}$, or $a_x = -1$ kt/sec.

It can be appreciated from the foregoing that the imposition of a "nominal" trim schedule does not detract in any way from the flexibility inherent in the basic set of redundant controls. Rather it provides a framework of standard activity and responses which is desirable in itself, and especially so in view of the resulting near-maximum performance and other good flight qualities.

2. Manual Control with Interconnect

The nearly constant shape of the δ_ν vs. δ_F relationship (Fig. 6) offers the possibility of a flap-nozzle interconnect that will provide approximate trim throughout any transition regardless of off-nominal throttle or nozzle settings. Suppose, for example, that either a nozzle or throttle bias is used to initiate a roughly uniformly decelerating transition. In either event (as discussed above), the flap-nozzle schedule required to maintain such deceleration has the same basic umbrella shape shown in Fig. 6. With a corresponding flap-nozzle interconnect, and a means for providing a nozzle-bias, the pilot has only to lower flaps with decreasing speed in accordance with the basic flap schedule. The appropriate nozzle to maintain desirable trim will be provided automatically by the interconnect.

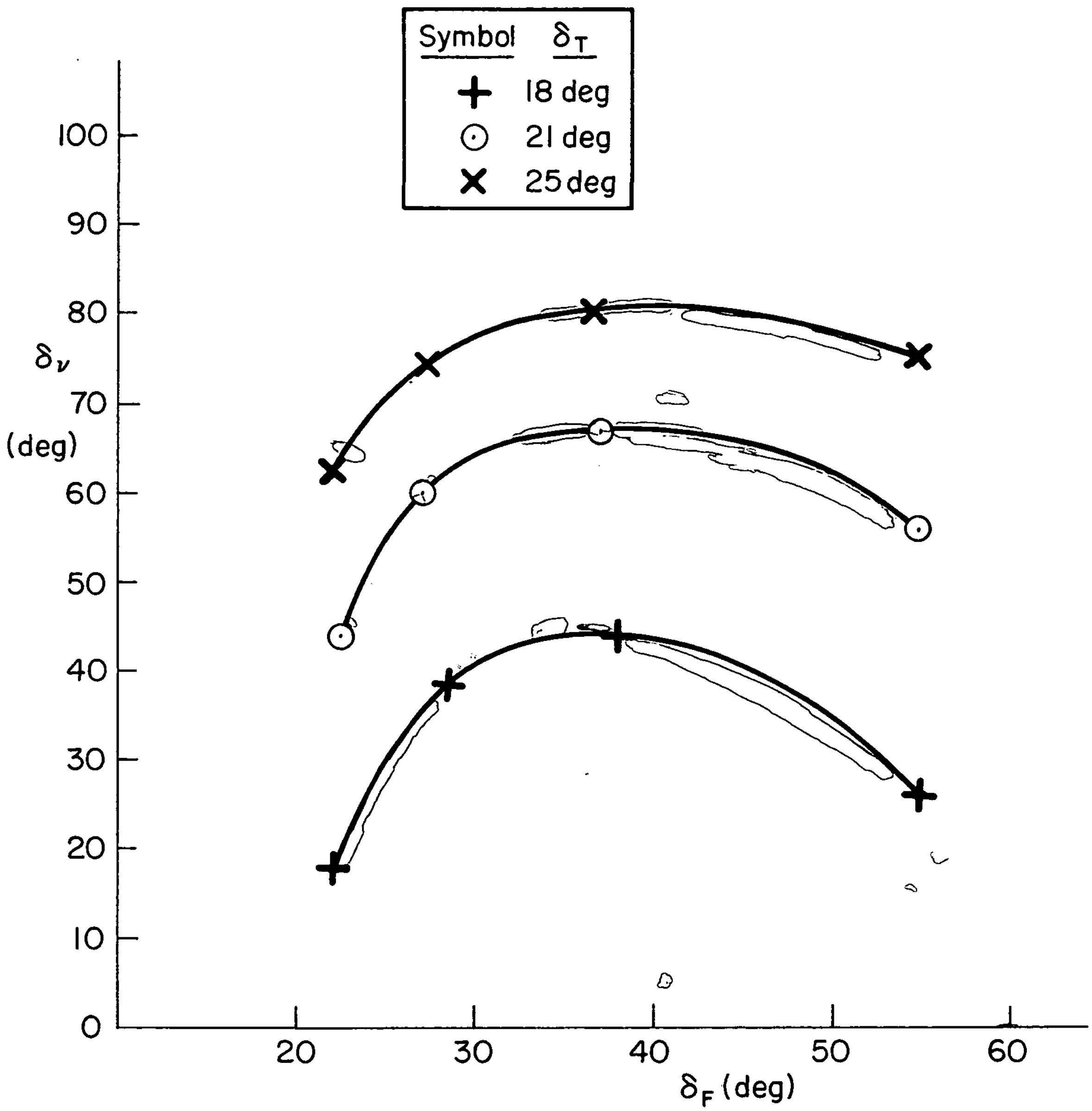


Figure 6. Flap-Nozzle Relationships for Level Flight ($\gamma = a_X = 0$) Transition

3. Automatic Configuration (and Speed) Control System

The ultimate pilot relief from trim management workload is attainable by utilizing the interconnect as the basis for an automatic trim management/command system. The sequential considerations of importance in developing the system are:

a. The flap, and interconnected nozzle, should be programmed as a function of speed.

b. Because premature flap deflections cause "ballooning," it is desirable for the flap to lag, rather than lead, speed changes.

c. Flap actuation is slower than nozzle actuation; therefore, use the flap to drive the nozzle (for trim).

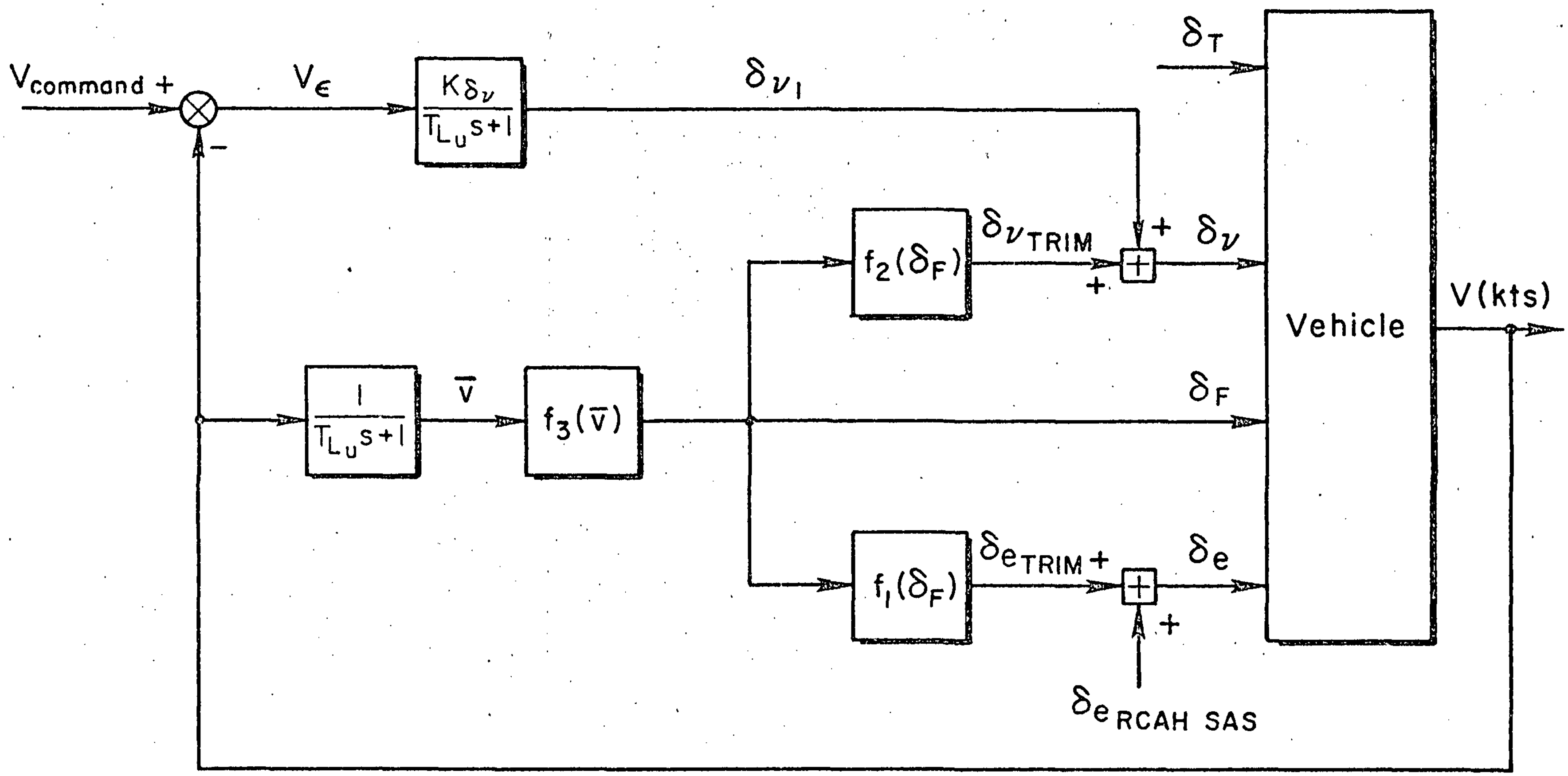
d. To complete the configuration management picture, use the flap to also drive the elevator (for trim).

e. Speed regulation and command (acceleration/deceleration) is best accomplished with the nozzle. (See later discussion of piloting technique.)

In summary, for trim, drive the flap with speed, and nozzle and elevator with the flap. (This will insure a desirable vehicle configuration at all speeds, and there will be no ballooning.) For speed control use the velocity error to additionally bias the nozzle. This control logic is depicted as:

$$\begin{tikzcd}
 & & & & & & \delta_{e_{TRIM}} \\
V_c \arrow[r] & V_\epsilon \arrow[r] & \Delta\delta_\nu \arrow[r] & \dot{V} \arrow[r] & V \arrow[r] & \delta_F \arrow[ur] \arrow[dr] & \\
 & & & & & & \delta_{\nu_{TRIM}}
\end{tikzcd}$$

The system block diagram is shown in Fig. 7. As noted in Fig. 7, the trim functions (f_1, f_2, and f_3) utilized in mechanizing the automatic configuration management system are obtained from the curves in Fig. 8 (which includes the $\delta_T = 21^\circ$ curves in Fig. 5). As previously observed, a throttle change from this nominal condition has hardly any effect on the "correct" f_3 function relating δ_F to speed (see Fig. 5); and only a small effect on the f_2 function relating $\delta_{\nu_{TRIM}}$ to δ_F. However, the (correct) $f_3 \times f_1$ product relating $\delta_{e_{TRIM}}$ to speed does change with throttle changes in almost direct ratio to the trim angle of attack variations depicted in Fig. 5. The



Note: f_1, f_2 and f_3 are functions derived from the trim curves for $\delta_T = 21$ deg (for $120 > V > 60$ kts)

Figure 7. Schematic Block Diagram of Automatic Speed Control System (Actuator Lags Are Not Shown)

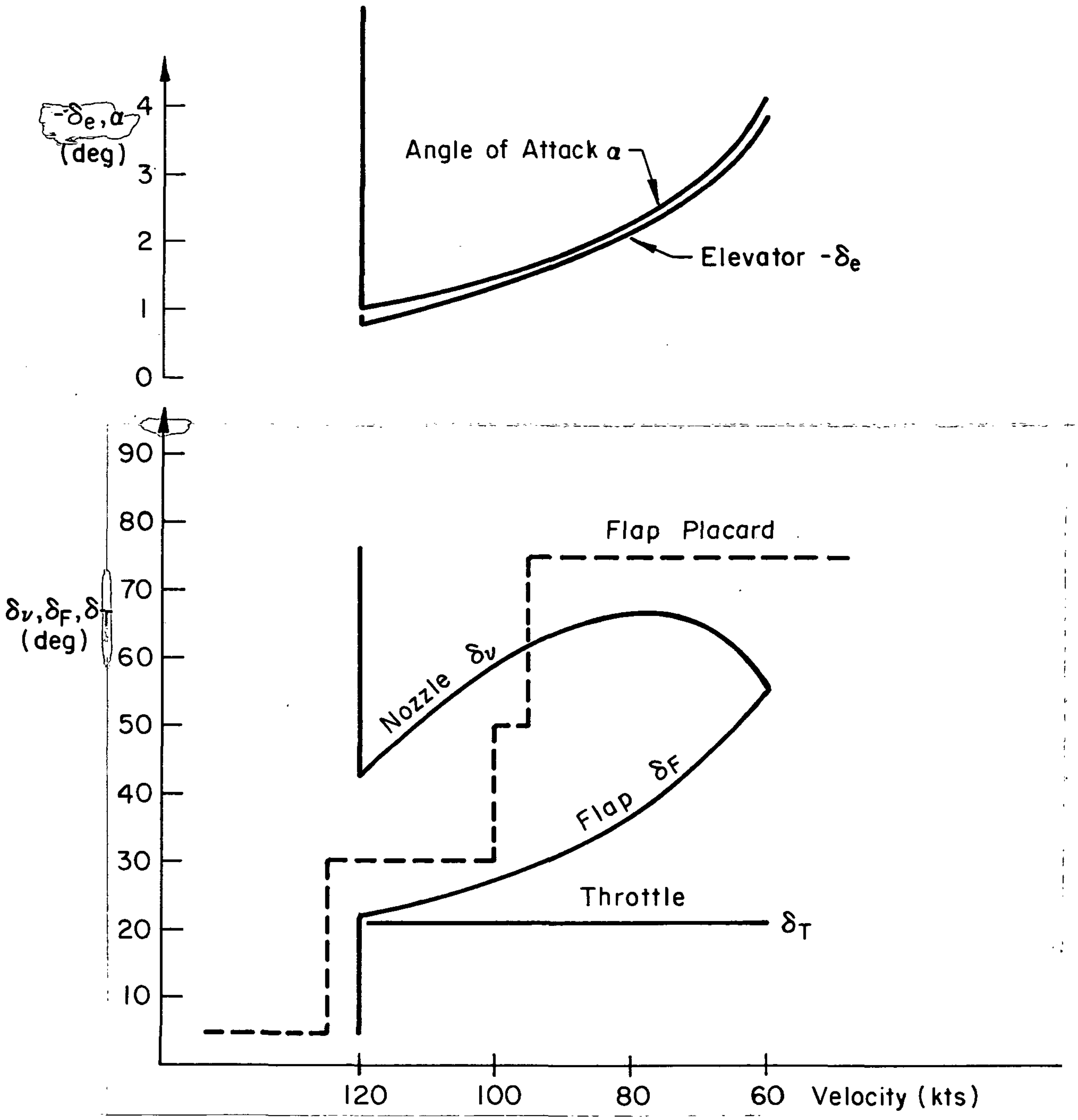


Figure 8. Vehicle Configurations During Conversion to STOL and Nominal Transition with $\gamma = a_x = 0$. (Note that conversion to STOL at 120 kt occurs at essentially constant elevator position.)

speed error feedback to δ_V will automatically handle the minor perturbations in the trim nozzle ($\delta_{V_{TRIM}}$) schedule occasioned by such off-nominal thrust conditions; and the use of a pitch rate command, attitude hold, series, inner SAS loop, as indicated in Fig. 7, will handle the variations in $\delta_{e_{TRIM}}$. The $1/(T_{L_u}s + 1)$ elements in the V_ϵ and forward V loop were included to "filter" undesirable gust components.

Figure 9 illustrates the response properties of the system to velocity command perturbation inputs about the 80 kt trim condition, for essentially constant θ, as would be obtained by either a rate-command attitude-hold SAS or by normal pilot regulation of attitude. To obtain this plot the f_1, f_2, and f_3 functions at 80 kt were approximated by linearized "derivatives" from the Fig. 8 summary plot of the nominal trim conditions. The break frequency of 0.8 rad/sec is considered quite adequate for a speed control loop (Ref. 5). The fact that the dc gain is not exactly unity is of little real concern since the command system can easily accommodate built-in compensation for possible steady errors. As a matter of fact, the magnitude of the steady error indicated in Fig. 9 is apparently an artifact of the linearization process; for in the complete nonlinear airplane simulation the error was considerably less, as noted later. Additional analysis of the speed SAS is presented in Ref. 2.

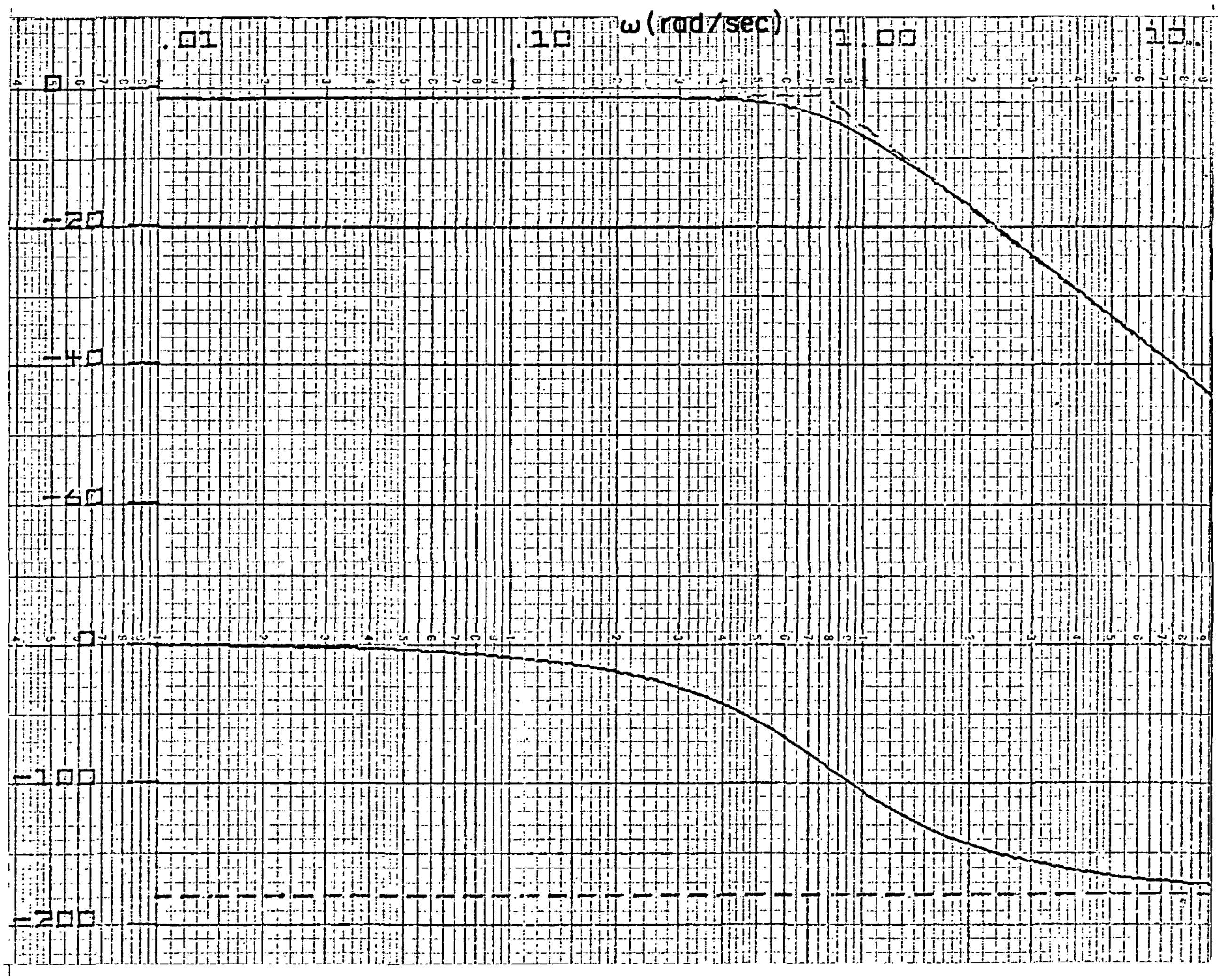


Figure 9. Bode Plot of $V/V_c\Big|_{\text{Closed Loop, with RCAH SAS}}$ at V = 80 kt

SECTION III

SIMULATION PLAN

A basic simulation experiment was developed to investigate and assess the above enumerated possibilities for improved trim management and glide slope control on the NASA Ames FSAA facility. In addition, to further improve the manual control manipulations, a set of modified cockpit controls was configured as follows.

- Throttle and nozzle levers (overhead for the standard configuration) were also located on the center console. (See Figure 10.) What is conventionally used as a console throttle lever was used for nozzle control, and the "usual" spoiler lever was used as a throttle lever.

- A thumb-actuated three-position switch was mounted on the console nozzle lever. The "trim button"-like switch was used to drive either the flap motor or the commanded airspeed (depending on the configuration being simulated).

The purposes of these changes was to put the control levers (switch) in a more convenient location for the pilot to use.

A. TASK OUTLINE

In addition to accomplishing the level flight transition manuever to 60 kt (corresponding to the Fig. 8 trim schedule) the pilot was also required to acquire and track the -7.5° glide slope and on certain runs to flare and land. Glide path acquisition and tracking was an IFR task with breakout at about 200 ft altitude. Flare and touchdown were to be accomplished VFR. Conventional instrument displays were utilized (see Fig. 10) for simulated IFR conditions, and a flight director indicator (Ref. 1) was used for glide slope tracking at 60 kts.

The transition "manuever" itself was, furthermore, to be subjected to detailed examination as to controllability. That is, the pilot's ability to stop transition at any point, hold speed or return to a higher speed condition, or proceed with speed reduction, etc. was to be investigated and assessed.

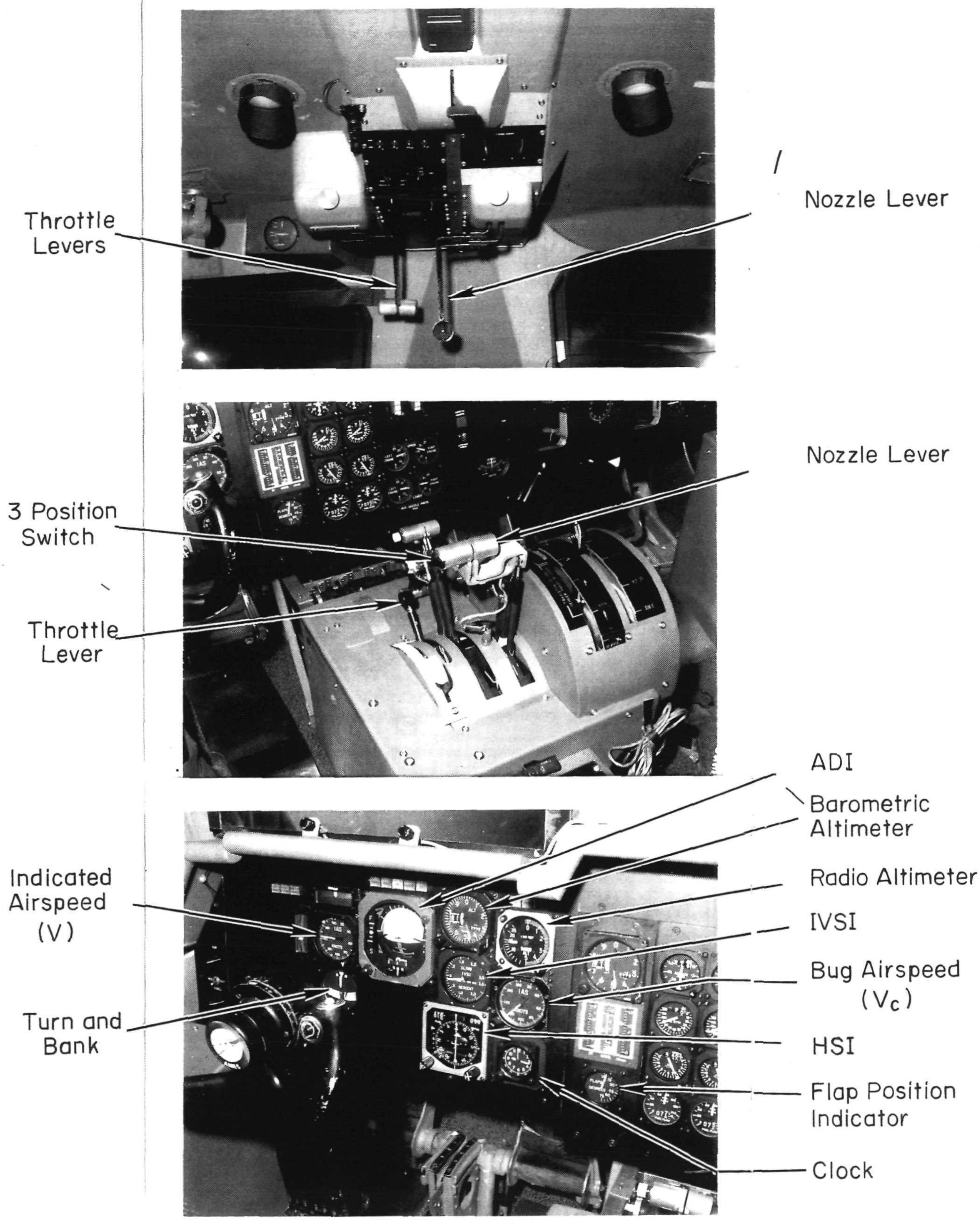


Figure 10. Views of Overhead and Console Control Levers, and Cockpit Instruments

B. CONTROL SYSTEM TYPES AND OPERATIONAL IMPLICATIONS

The various control systems available to effect the foregoing task elements were as follows.

1. Manual — overhead ("standard") control levers for nozzle, throttle, and flap (with detents).

2. Manual — improved control levers.

   The nozzle and throttle levers were moved down from their overhead location to the center console as noted earlier. The "usual" console throttle lever was used as a nozzle control, and the "usual" console spoiler handle was used as a throttle lever. In addition, the console throttle sensitivity (i.e., thrust output per degree of lever) was reduced to about half that of the overhead ("standard") throttle to improve accuracy and ease of setting.

   The flap control was also moved down to the console in the form of a switch (which ran the flap drive motor) located near the top of the nozzle lever, and operated by the pilot's thumb. This meant that for constant-throttle transitions the pilot could leave his right hand on the nozzle lever throughout the transition, and he could "beep" in flap as desired.

   These "improved" control levers (and thumb switch) were also used in the "manual with interconnect" and "automatic" control modes of operation. In all other respects the airplane simulation was essentially as reported and documented in Refs. 4, 7, and 8.

A step-by-step listing of the manual control events that take place from cruise through to touchdown, in amplification of the Fig. 8 schedule, is as follows:

<u>Cruise Configuration</u>

$h = 1500$ ft	$\delta_V = 6$ deg
$\gamma = 0$	$\delta_T = 14$ deg
$V = 140$ kt	$\alpha = 4.4$ deg
$\delta_F = 4.5$ deg	

Conversion to STOL

- The nozzle is set at 76 deg to initiate deceleration.
- As the vehicle decelerates through 130 kt the throttle is advanced to 21 deg.
- With 76 deg nozzle and 21 deg throttle the vehicle will decelerate to 120 kt (where it will be in trim with an angle of attack of 5.4 deg and 4.5 deg flaps).
- Flaps are lowered to 22 deg and nozzle is reset to 43 deg. (Speed stays at 120 kt, but pitch attitude and angle of attack are lowered to one deg.)

Transition

- Nozzle is set to 70 deg to produce a deceleration.
- As vehicle decelerates at about 1 to 2 kt/sec, the flaps are lowered per the plot in Fig. 8. Altitude is held constant with attitude.
- To stop the deceleration at any point, nozzle is reset to the Fig. 8 trim value, e.g., at 60 kt the nozzle is reset to 55 deg to terminate transition.

Post-Transition Configuration

h	=	1500 ft	δ_ν	=	55 deg
γ	=	0	δ_T	=	21 deg
V	=	60 kt	α	=	4.0 deg
δ_F	=	55 deg			

Glide Slope Acquisition and Tracking

- At about 1/2 dot below the glide slope the nose is pushed down, the flaps are lowered to 75 deg, and the nozzle is set to 94 deg.
- Speed is now maintained at 60 kt with attitude, and beam deviation is controlled with nozzle.

Glide Slope Configuration

γ	=	−7.5 deg	δ_T	=	21 deg
V	=	60 kt	θ	=	−9.5 deg
δ_F	=	75 deg	α	=	−2 deg
δ_ν	=	94 deg			

Flare

- The nozzles are rotated aft to about 70 deg just prior to flare (at an altitude of about 100 ft) to minimize the speed bleedoff during flare (and prior to touchdown). At flare the nose is raised to give a pitch attitude of about zero deg.

3. Manual with Interconnect

In this mode the crossfeeds from the flap to the nozzle and elevator provide the required nozzle and elevator trim. Thus, the pilot puts in the appropriate amount of flap for the speed he desires, and the corresponding trim values of nozzle and elevator are automatically provided via the crossfeeds. (The trim nozzle and elevator that go with any given flap position can be determined from Fig. 8.) This simplifies the control task and reduces the pilot workload.

If the overhead flap lever (which has appropriate detents) is used instead of the thumb switch, then the flap is usually lowered in discrete amounts (rather than more-or-less continuously), but the corresponding trim values of nozzle and elevator are still provided by the crossfeeds. However, the pilot may now prefer to provide his own elevator trim in order to eliminate the unwanted pitching moments that arise when sudden large flap changes are made. These pitching moments are caused by the elevator trim changes that accompany the flap changes at essentially constant speed (but which may not be required until after the speed has changed to the value associated with the new flap position).

As mentioned above, the crossfeed provides the appropriate nozzle for trimming the vehicle at $\gamma = a_x = 0$ (at any desired speed). However, to accelerate or decelerate requires an additional input by the pilot. The choice of nozzle as the most effective available input for achieving gross speed control is based on the possibilities listed below in order of increasing preference.

$\dot{V} \rightarrow \delta_e$

- Results in ballooning.
- Control power and bandwidth of $h \rightarrow \delta_e$ are both higher than for $h \rightarrow \delta_\nu$. Therefore, δ_ν is not a very effective means to counteract the ballooning induced by δ_e.

$\dot{V} \to \delta_F$

- Results in ballooning [due to $Z_{\delta_F}\delta_F$ and $M_{\delta_e}(\delta_e/\delta_F)\delta_F$ — if present].

- Attitude is effective in counteracting ballooning but requires large pitch changes.

$\dot{V} \to \delta_T$

- Good accelerator/decelerator when nozzle is pointing aft.

- Not good accelerator/decelerator when nozzle is pointing down (i.e., $V < 100$ kt). Further, when nozzle is pointing down, get large angle of attack and rate of climb (descent) problems.

$\dot{V} \to \delta_\nu$

- Involves only small pitching moments and no ballooning.

- Altitude control via attitude is effective.

Thus, the procedure contemplated for acceleration/deceleration control is for the pilot to bias the nozzle with a series input that sums with the built-in nozzle (flap) schedule. For example, to decelerate ("convert") from cruise at 140 kt to the STOL mode at 120 kt the "standard" nozzle angle of 76 deg is set by the pilot. This setting is consistent with the nozzle schedule (as a function of flap) because the schedule assumes that the pilot supplies the initial 76 deg. Accordingly, it does <u>not</u> constitute a bias input in the above context; however, to now decelerate from 120 kt does require a true bias to the normal nozzle schedule. This is taken care of by the pilot's adding roughly 20 deg of "extra" nozzle at 120 kt (to provide deceleration) and then removing this bias when he reaches 60 kt. Thus, the crossfeed takes care of trim, and the pilot only has to use the nozzle for deceleration. In addition, the pilot:

- Sets trim with the flap position (each flap angle has a particular speed associated with it), and

- During "constant"-speed flight phases, controls altitude with the nozzle and airspeed with attitude.

4. Automatic

In this control mode the pilot flies with elevator and throttle much the same as he would with a conventional front-side airplane. That is, altitude is controlled with attitude, and sink rate trim is controlled with throttle. The control system operates the nozzle (to provide acceleration and deceleration, as well as trim), the flap (to keep trim angle of attack within an acceptable range), and elevator (for trim) as shown schematically in the block diagram of Fig. 7. Thus, the control system not only controls speed, but it also controls the vehicle configuration to insure that it is within a "good" region of the overall window of possible configurations. To initiate or stop transition the pilot has only to set the button-operated speed-command "bug" at the desired speed.

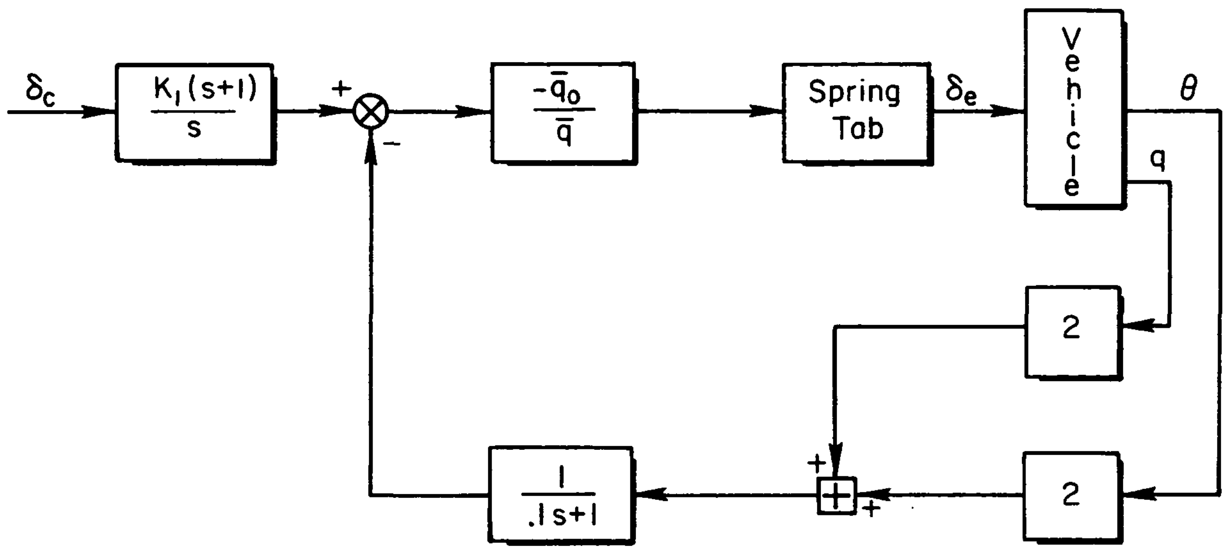
5. Pitch Rate Command Attitude Hold (RCAH) SAS

The above control configurations were usually flown through an inner-loop SAS shown schematically in Fig. 11. This portion of the total system improves the basically sluggish pitch response properties of the basic aircraft so they do not "interfere" with the basic transition management and (path) control aspects under study. The SAS is similar to others already reported (Ref. 7) and will not be further discussed in this report except to note that it supplies a steady pitch rate proportional to column position, in addition to holding the last commanded pitch attitude. That is, the RCAH SAS maintains the attitude existing at the time the pilot releases the control column or returns it to neutral (trim). For some of the automatic mode testing the inner-loop SAS was deactivated and only basic elevator control used to simulate a failed SAS. A complete analysis of the RCAH system concept is presented in Ref. 2.

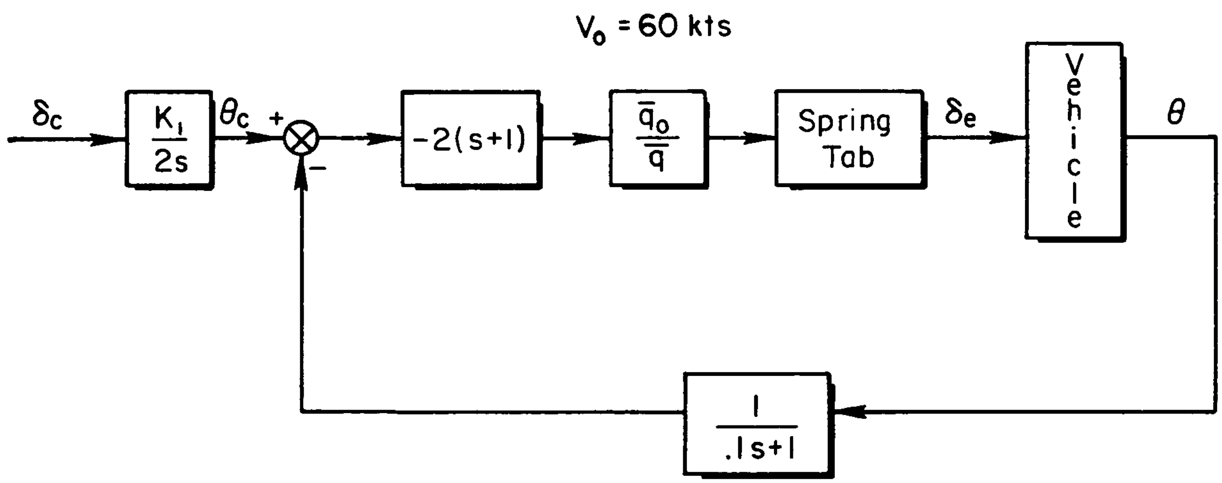
C. DISTURBANCE ENVIRONMENT

All of the configurations tested were first flown under "ideal" conditions of calm air. Later they were run again with high frequency* random gusts, steady winds and wind shears. The particular disturbances used were: gusts, $\sigma_{u_g} = \sigma_{v_g} = 4$ ft/sec; and the steady wind and shear shown at the top of page 31. The random gust intensity level was considered "light" by the participating pilots.

*Unfortunately, the random gust source available at the time of the experiments had very little power below 1 Hz.

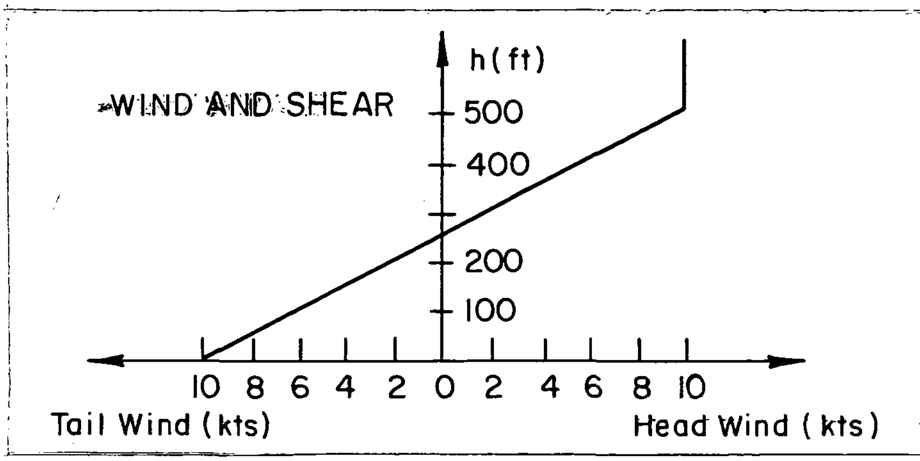


a) Actual Loop Structure



b) Equivalent Diagram

Figure 11.2 Block Diagram of Rate-Command Attitude-Hold Pitch SAS



D. TEST PROCEDURES AND TASKS

Three IFR STOL transition maneuvers were selected. These are consistent with a level flight transition, followed by the intersection of a 7-1/2 deg glide slope beam, acquiring and tracking the beam, breakout at 200 ft altitude, and then performing a visual flare and landing.

1. Nominal continuous transition

   This is a conversion to STOL (140 kt clean, down to 120 kt with 22 deg flap, 44 deg nozzle and 21 deg throttle) followed by continuous deceleration and configuration changes down to the post-transition flight condition. Glide slope acquisition, tracking, and flare follow.

2. Decelerate-stop-decelerate transition.

   This is a conversion to STOL followed by a deceleration to 100 kt. One hundred kt is then maintained while all transition transients die out. Then the vehicle is decelerated to 80 kt, where all transients are again removed. Finally, the vehicle is decelerated to 60 kt and again a steady condition obtained. Glide slope and flare are as before. The purpose of this task is to determine if any problems arise in terminating (or delaying) a transition once it has begun.

3. Decelerate-stop-accelerate transition

   This is a conversion to STOL followed by a deceleration to 80 kt and then a relatively rapid acceleration back to the cruise condition at 140 kt. The purpose of this is to determine if any problems arise when aborting a transition (at constant altitude).

During these various transitions, the different modes of control described above were compared and assessed. In addition, altitude control with throttle and nozzle were compared during glide slope tracking. Time histories were obtained for all test conditions and were supplemented by recorded pilot commentary. Pilot ratings using the Cooper-Harper scale (Ref. 9) were obtained for selected configurations from the two participating NASA test pilots.

SECTION IV

RESULTS

Table 1 provides a succinct summary of the significant comparisons obtained in the test time available. The overall ratings given in Table 1 reflect a steady improvement as the level of automation is increased, as expected. They also show that in general the defined transition corridor and schedule (interconnect) provide a major portion of the final improvement attained. Furthermore, some such level of improvement appears necessary to cope with commonly occurring winds and turbulence; i.e., as noted in Table 1, Pilot A found "fully manual control in a wind shear environment...an unacceptable situation." Selected time histories and additional pilot commentary illustrating and amplifying on the above trends are given below.

TABLE 1

MANUAL CONTROL IMPROVEMENT EVALUATIONS

FLIGHT CONTROL MODE	PILOT RATING				REMARKS
	STILL AIR		WIND SHEAR + GUST		
	PILOT A	PILOT B	PILOT A	PILOT B	
Manual a) Basic airplane	5		7		Manual control in wind shear environment is an unacceptable situation.
b) Defined transition schedules	3-4				
c) Simplified cockpit controls	4				
Manual with interconnects from flap to nozzle and elevator	3	2-3	5	3-3-1/2	Pilot A used overhead flap lever with detents, and Pilot B used thumb switch to drive flap motor.
Automatic	1-2	2-3	3	3	In still air Pilot B rated the transition (from 120 kt to 60 kt) as 2, and the conversion to STOL (140 – 120) as 3.

Figure 12 is an example of a typical time history, in this case for a manual approach utilizing the flap/nozzle schedule in smooth air and also employing the overhead control arrangement. This run was made after considerable practice and familiarization with the basic interconnect system and automatic modes of control, so that the pilot had pretty well learned how to fly the airplane. (In fact as a result of this learning process, Pilot A changed his rating from a 5 to a 3-4.) It may be seen that the transition maneuver was stopped at 80 kt and held for a considerable length of time and then continued down to 60 kt where the glide slope was intercepted through a pitchover attitude change. The glide slope tracking exhibited is quite good, and as indicated by the fairly constant θ trace and the active nozzle trace, it was controlled primarily by use of the nozzle. In addition, however, the pilot did use throttle, as evidenced by the hot thrust and throttle position variations shown in the lowermost trace. This trace also indicates that the hot thrust follows the throttle motion with reasonable fidelity. (On later figures, there is no δ_T trace but, as shown here, it bears a close resemblance to the hot thrust trace which is contained in all the remaining figures.) It is pointed out that the occasional large "bumps" in the $\dot{h}$ trace that seem to occur when no inputs are applied are in fact responses to step increments in flap extension. At the end of the run it may be seen that the flare maneuver was accomplished by pulling up in attitude and decreasing the nozzle angle to provide more thrust. Notice, as a result, that the airspeed is quite constant throughout the flare until touchdown. Notice also that for the entire run the throttle was used quite sparingly in that the major portions of the run are at nearly constant values of thrust.

Pilot comments follow.

- The decelerate-stop-decelerate task performed manually gives too much workload. The task with three controls (δ_F, δ_V, δ_T) is too much.
- The vehicle is "more fun manually," but performance capability is restricted. You cannot go to a desired speed easily (manually), and you probably couldn't do it in gusty air. The workload is too high.
- The rating change from a 5 to a 3-4 (noted above) doesn't reflect the smaller head- and tail-wind envelope that exists with manual control.

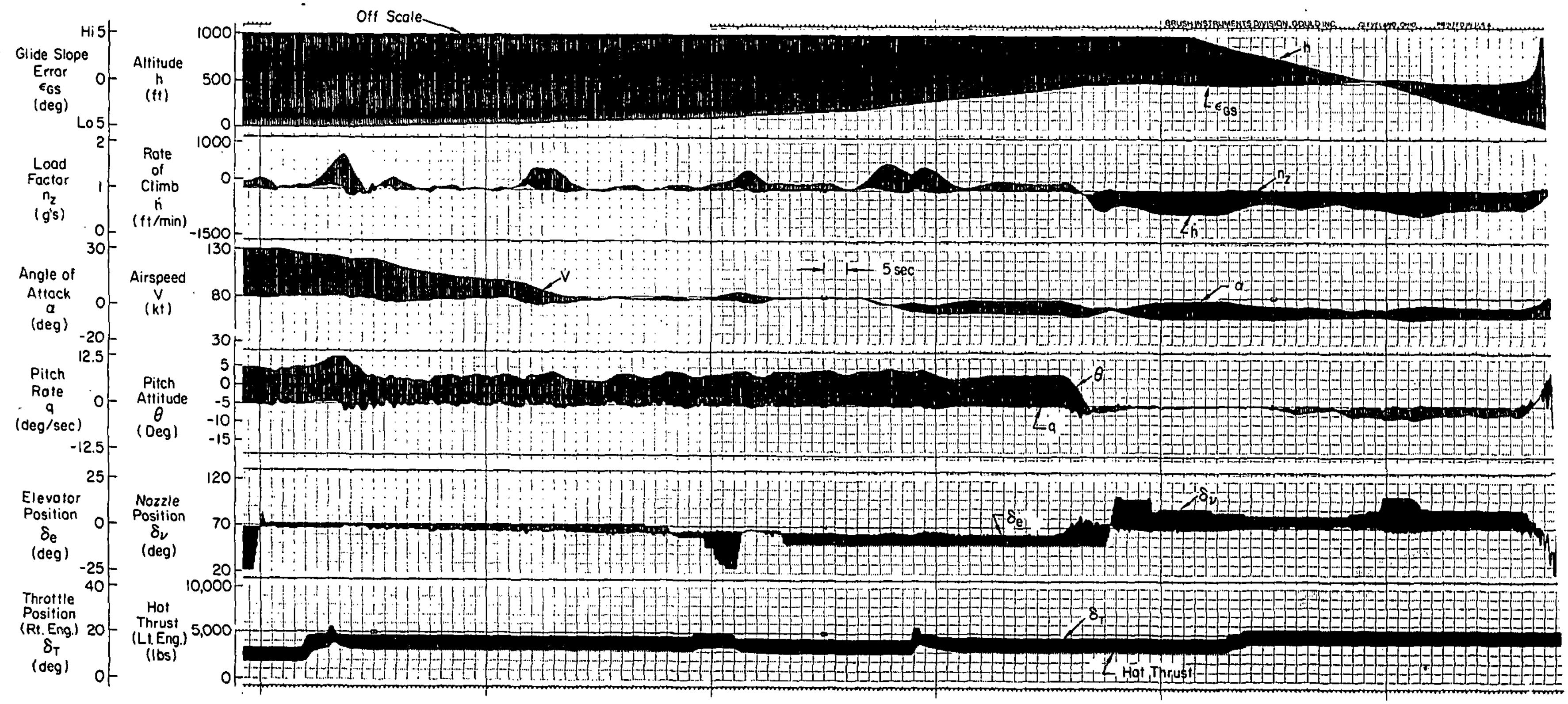


Figure 12. Manual with Schedule, Smooth Air, Overhead Control

- The nozzle indicator should be on the same meter as the flap indicator — and displayed in a way that tells the pilot at a glance when nozzle and flap are correctly "synchronized" and when they are not. Thus, the pilot would know how to get "back" to the proper nozzle position for any given flap setting.

Figure 13 illustrates still air, manual control with the interconnect. In this case, the pilot transitioned to only about 80 kt before acquiring the glide slope. Glide slope acquisition and a simultaneous reduction in speed to about 60 kt were obtained by a sharp pitchover preceded by lowering the flaps, all at constant thrust. This fairly rapid maneuver did result in some speed variations which the pilot then attempted to remove using thrust. This mode of speed control was obviously unsatisfactory and resulted in the speed reversals previously cited, that is, reducing nozzle thrust resulted in a speed buildup. Accordingly, this form of control was abandoned with the pilot reverting to constant thrust and utilizing the nozzle, as indicated. With nozzle control, glide slope tracking and speed maintenance were fairly well held.

The pilot's comments reflect these observations, i.e.,

- $h \rightarrow \delta_T$ not very effective because a reduction in throttle caused vehicle to speed up. Leave power alone on glide slope (with manual or manual with interconnect modes).

- 60 kts too slow to intercept the glide slope beam; 80 kt better. If you fly at 60 kt and lower the flaps to 75 deg, you need to push the nose down very quickly to avoid losing too much speed; but, if you intercept at 80 kt, you cannot descend at −7-1/2 deg <u>and</u> decelerate to 60 kt. Thus, the speed corridor to intercept the glide slope beam is too narrow (using manual or manual with interconnect modes).

Figure 14 is a plot of the same pilot again flying manual with interconnect but this time subjected to turbulence and shear disturbances. The same basic transition to 80 kt, followed by glide slope acquisition and attendant speed reduction with pitchover and increased nozzle deflection are evident. Throughout this run the pilot maintained essentially constant thrust except during a limited portion of the glide slope tracking where apparently the shear winds were somewhat troublesome. Notice in this connection that the pilot was possibly confused, because he could have used considerably more nozzle deflection than he did. Notice also that this particular run involved somewhat higher angles of attack and pitch attitude than the preceding Fig. 13 run.

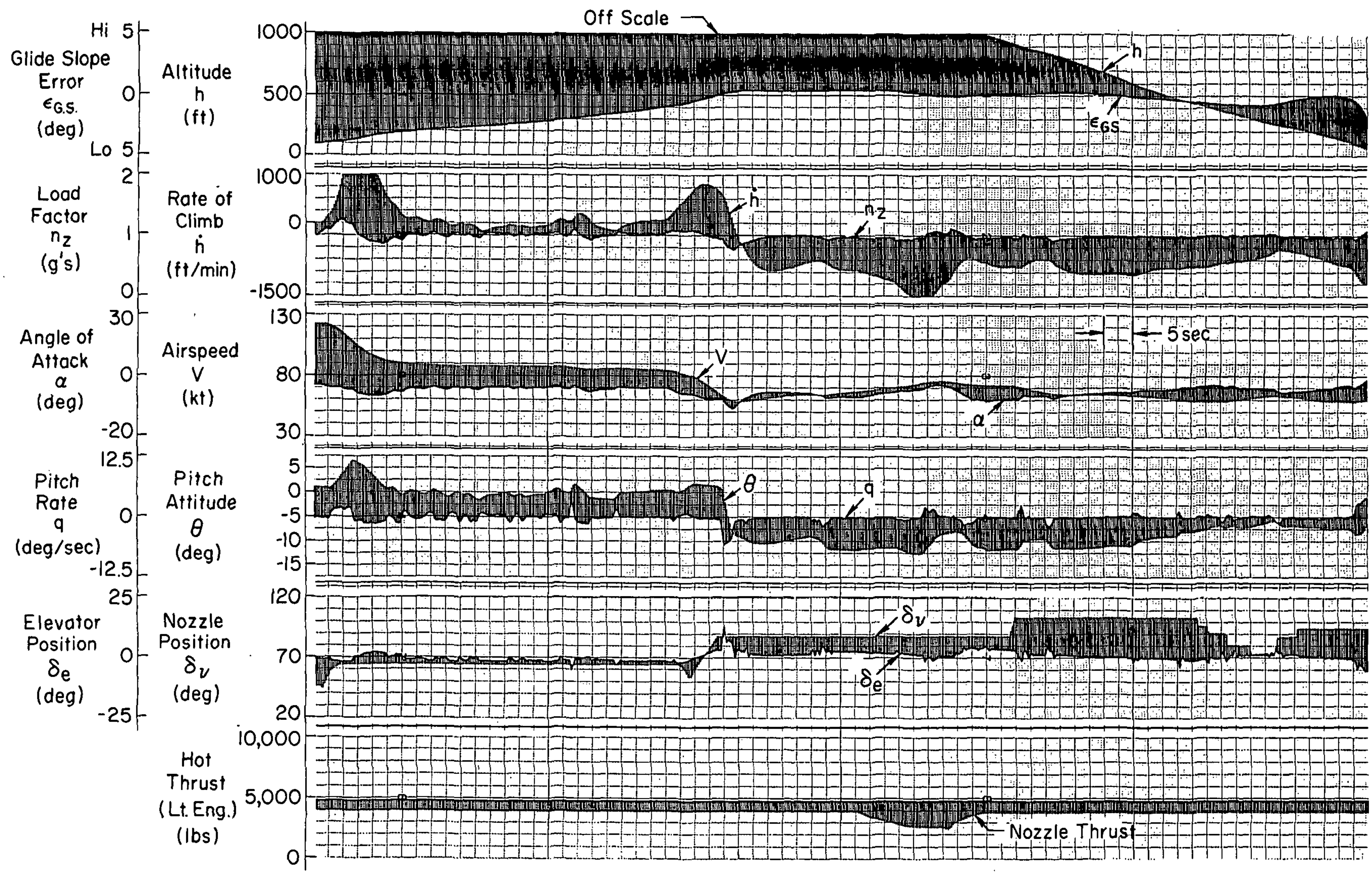


Figure 13. Manual with Interconnect, Still Air, Console Control, Pilot A

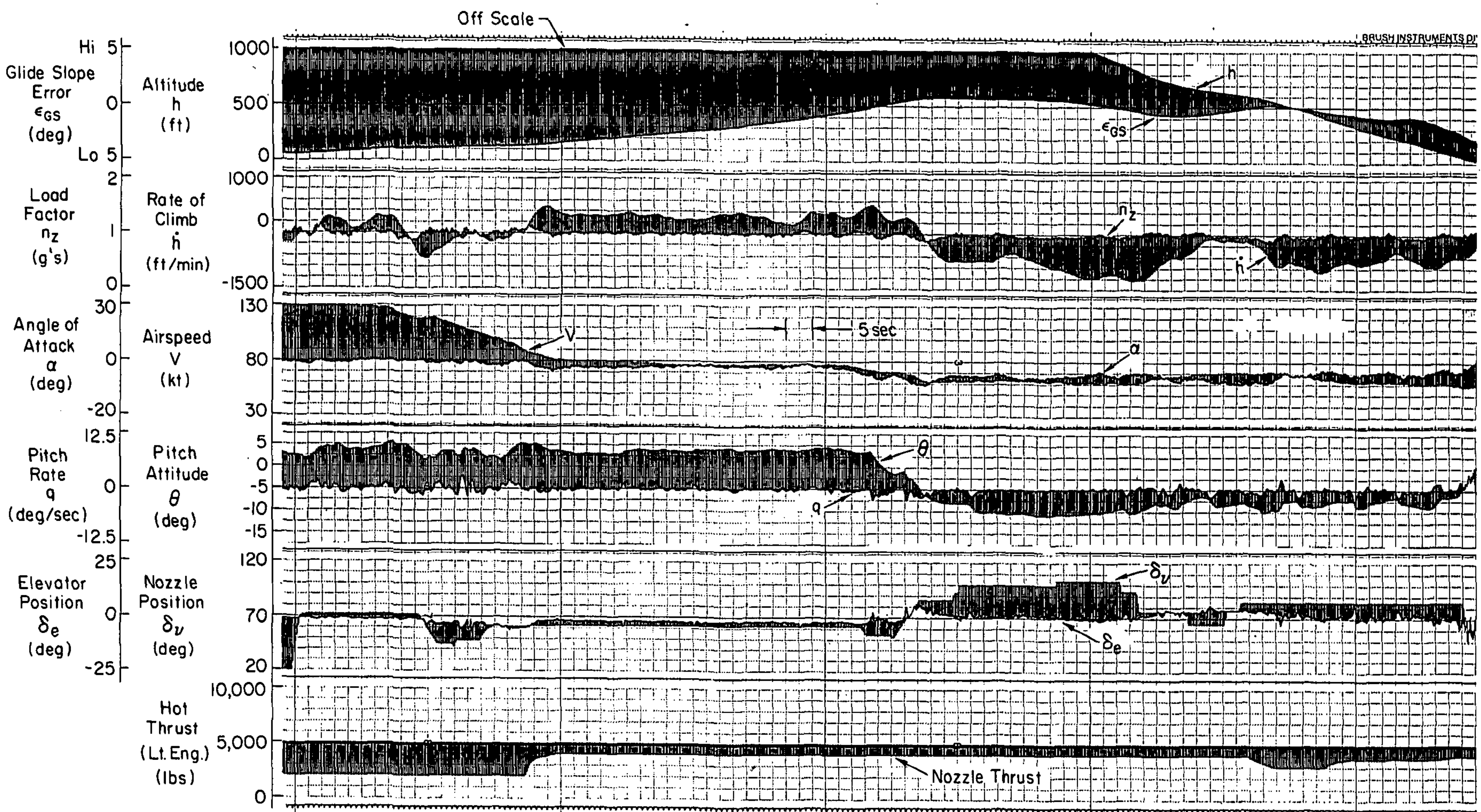


Figure 14. Manual with Interconnect, Turbulence and Shear, Console Control, Pilot A

Additional general Pilot A commentary on the manual and manual with interconnect mode follows:

- On the 7-1/2 deg glide slope there is not sufficient descent capability with nozzle (only about an additional 400 ft per min). But get even less descent capability with less than 75 deg flap.

- Doesn't like the button flap control because there are an infinite number of flap positions possible; and doesn't like to have to look at the flap gauge. He wants only a few possible flap positions. Thus, he likes the overhead flap lever that has detented positions better.

- Summarizing the manual with interconnect mode, it is easy to decelerate and intercept the glide slope, but γ control on glide slope is poor. It is, however, an improvement over purely manual control.

Figure 15 represents a run similar to the last except that it was conducted by Pilot B rather than Pilot A. In this case, the transition to 60 kt is completed before the glide slope is acquired. The nozzle thrust is held constant throughout the entire maneuver. The glide slope, as before, is acquired with a pitchover and a nozzle angle increase. Nozzle control of the glide slope is evident, but it is only fair, in that a low-frequency ϵ_{GS} oscillation is evident. Notice that α, θ, and $\dot{h}$ perturbations are somewhat lower than those of the preceding run.

Figure 16 is essentially a duplication of the preceding figures except that in this case overhead flap control was utilized rather than the flap button on the console. The runs are quite similar except that Fig. 16 indicates a little more nozzle activity during the transition and glide slope tracking portions of the flight. Glide slope tracking, on the whole, appears also to be a little more consistent than in the previous trial.

The following pilot commentary is applicable to Figures 15 and 16:

- With the flap on the thumb button he could hold attitude better (no large transients). Prefers button to detent control.

- A better technique to use when acquiring the glide slope beam is to fly at 70 kt (instead of 60) until ready to start descending. Then put down 75 deg of flaps (from 55 deg) and push over as vehicle slows down to 60 kt. In this way you don't need to push over so quickly, and the maneuver is no longer critical.

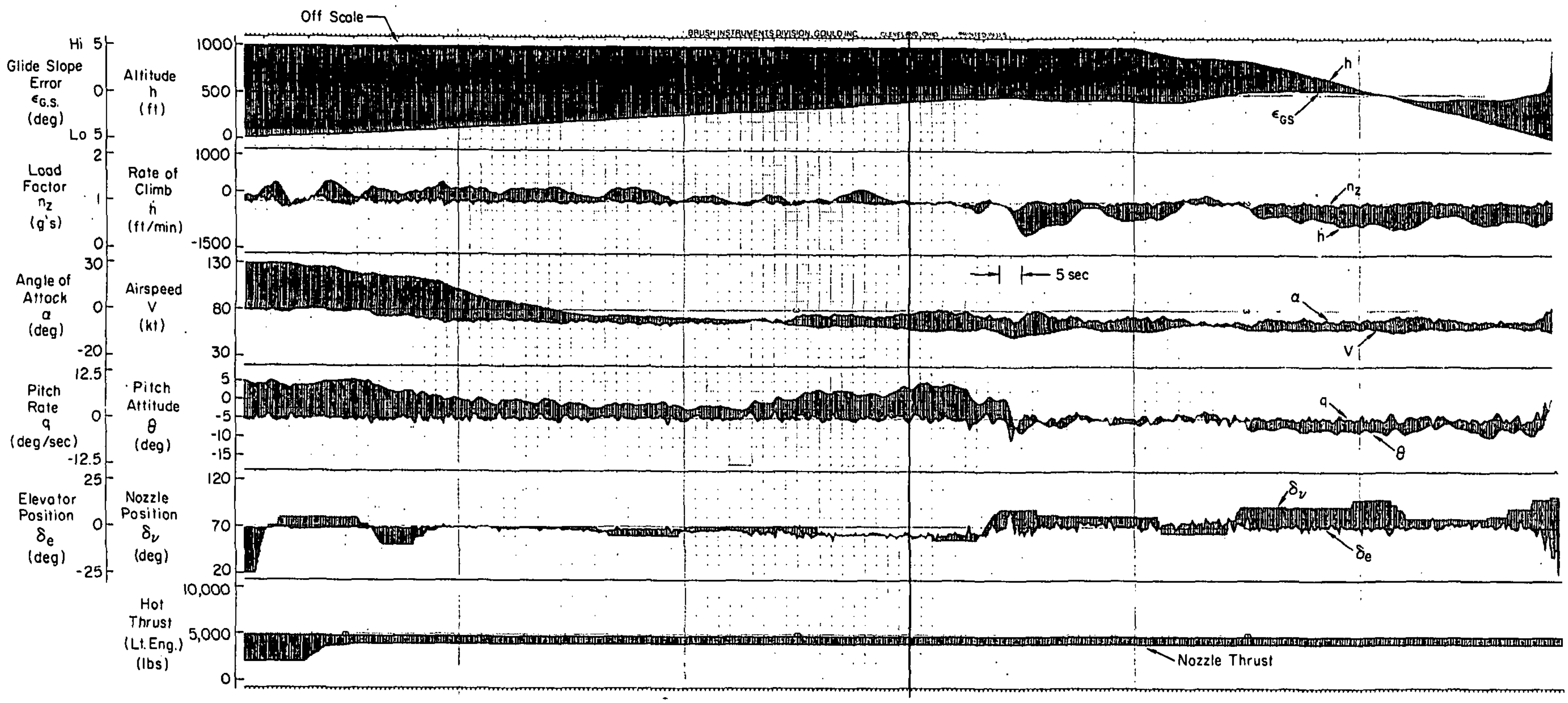


Figure 15. Manual with Interconnect Mode, Turbulence and Shear, Button Flap Control, Pilot B

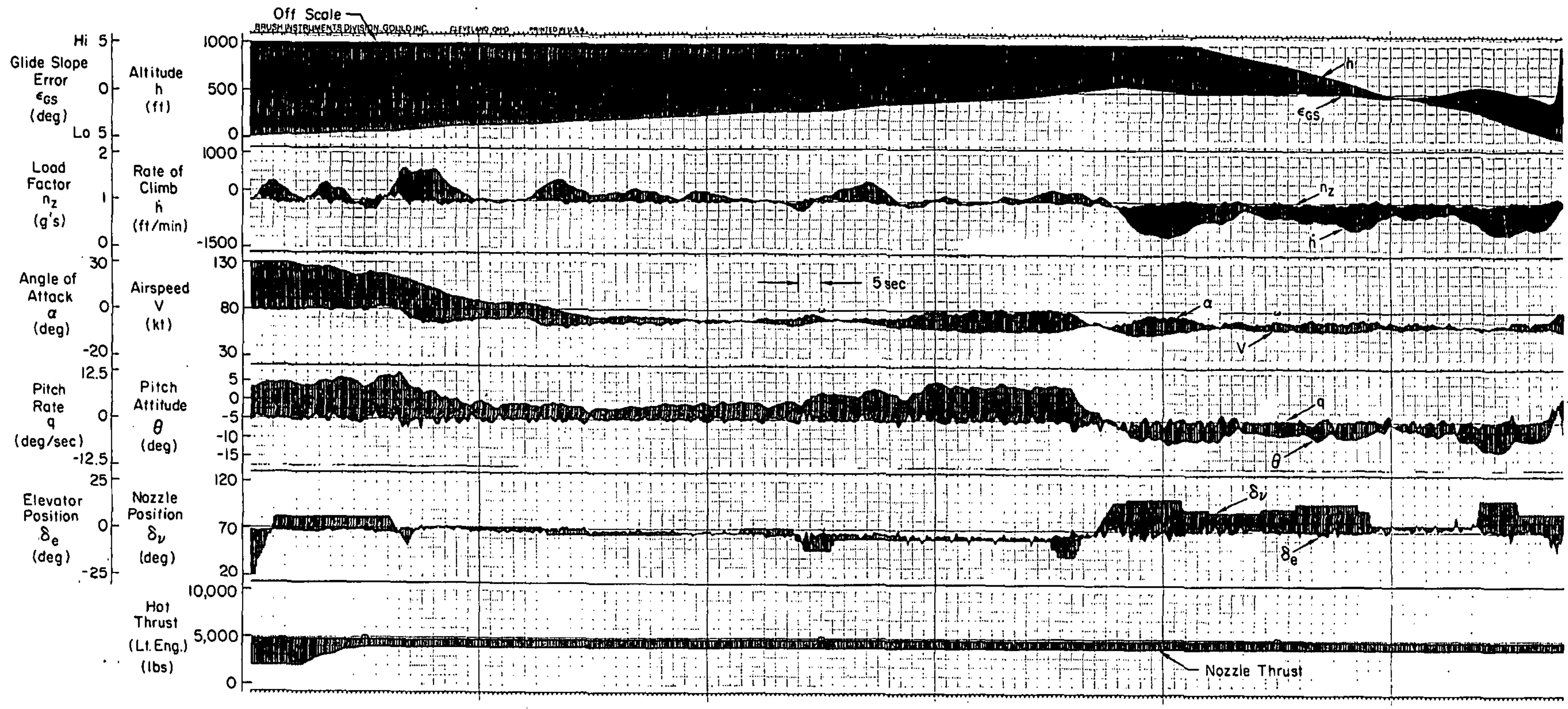


Figure 16. Manual with Interconnect Mode, Turbulence and Shear, Overhead (Detented) Flap Control, Pilot B

Figure 17 also shows the manual control with interconnect using the detented flap. In this case, however, the task was simply to stop the transition and return to level flight at 140 kt (deceleration-acceleration). The transition was stopped at 80 kt and the entire maneuver was accomplished with nozzle thrust held constant. There is little evidence here that the pilot attempted to control $\dot{h}$ deviations with the nozzle. Rather, it seems he was using θ to control $\dot{h}$. Of course, for the minimum speed shown (80 kt), such a technique is feasible because the aircraft is still (barely) on the front side of the drag curve.

Figure 18 is a record of glide slope control with the automatic mode but without an inner-loop SAS operating. In this case, the pilot attempted to control on the glide slope with throttle, as evident by the lowermost nozzle thrust trace. Notice that now the airspeed variations are not particularly troublesome despite the use of thrust because of the speed-holding features of the automatic mode.

Figure 19 is a run similar to the preceding except that the pilot here is using attitude (through elevator) to control glide slope rather than throttle. (Nozzle thrust was held constant.) In general, this mode of control resulted in smaller α, n_z, V, and $\dot{h}$ perturbations than did use of the throttle. A further point of interest in comparing these two figures is the fact that the attitude time histories look quite similar to the nozzle thrust time histories in Fig. 18, that is, to maintain glide slope appears to require similar kinds of input timing. In fact, these two figures demonstrate that with the automatic system the pilot has a choice of primary control and that he can use either throttle or attitude to regulate glide slope deviations.

The pilot commented that he

- Likes (and uses) $h \rightarrow \delta_e$ on glide slope with the speed-command system. It makes it a nice flying airplane even without the SAS.

Figure 20 is an example of the fully automatic mode, in this case as utilized in a decelerating, stopping, accelerating, transition maneuver. The first, short, stop at about 105 kt is not as clean as it might be, apparently because the nozzle thrust had not yet been set at its proper value, as evidenced in the lower trace. However, once set at a constant value, the remaining

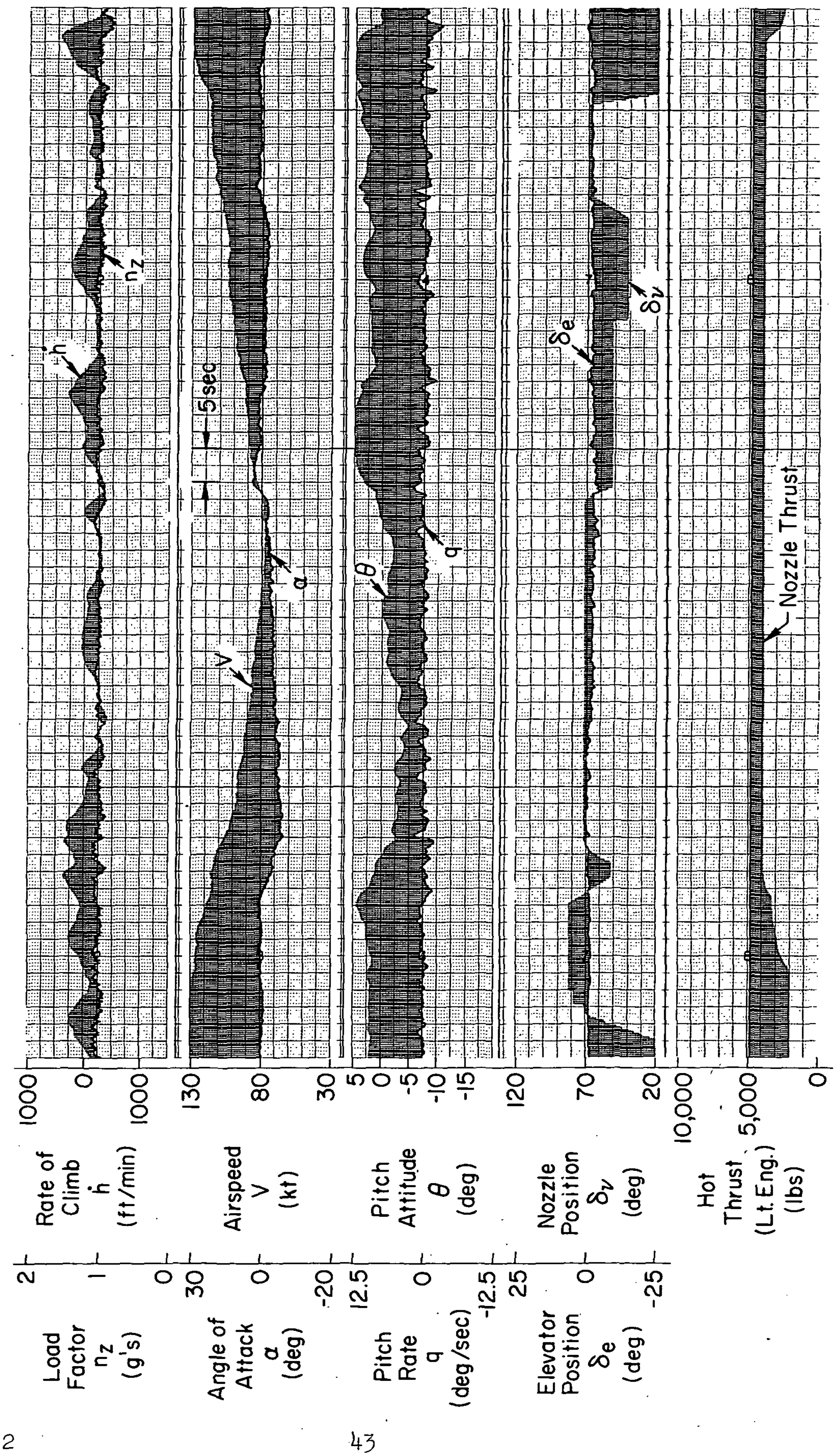


Figure 17. Manual with Interconnect, Turbulence, Detented Flap, Decelerate/Accelerate, Pilot B

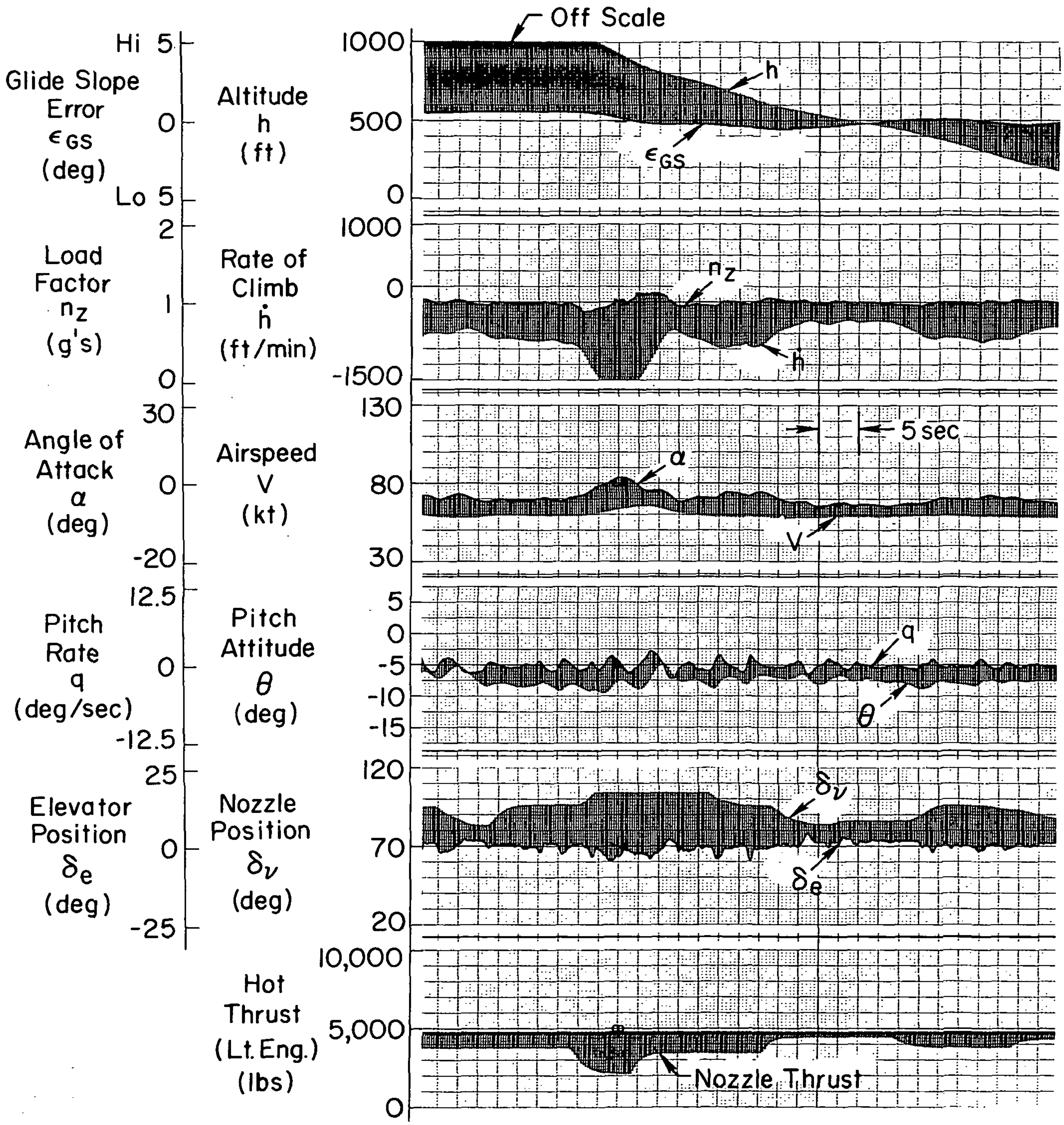


Figure 18. Automatic Mode, No SAS, Turbulence and Shear, Glide Slope Control with Throttle, Pilot B

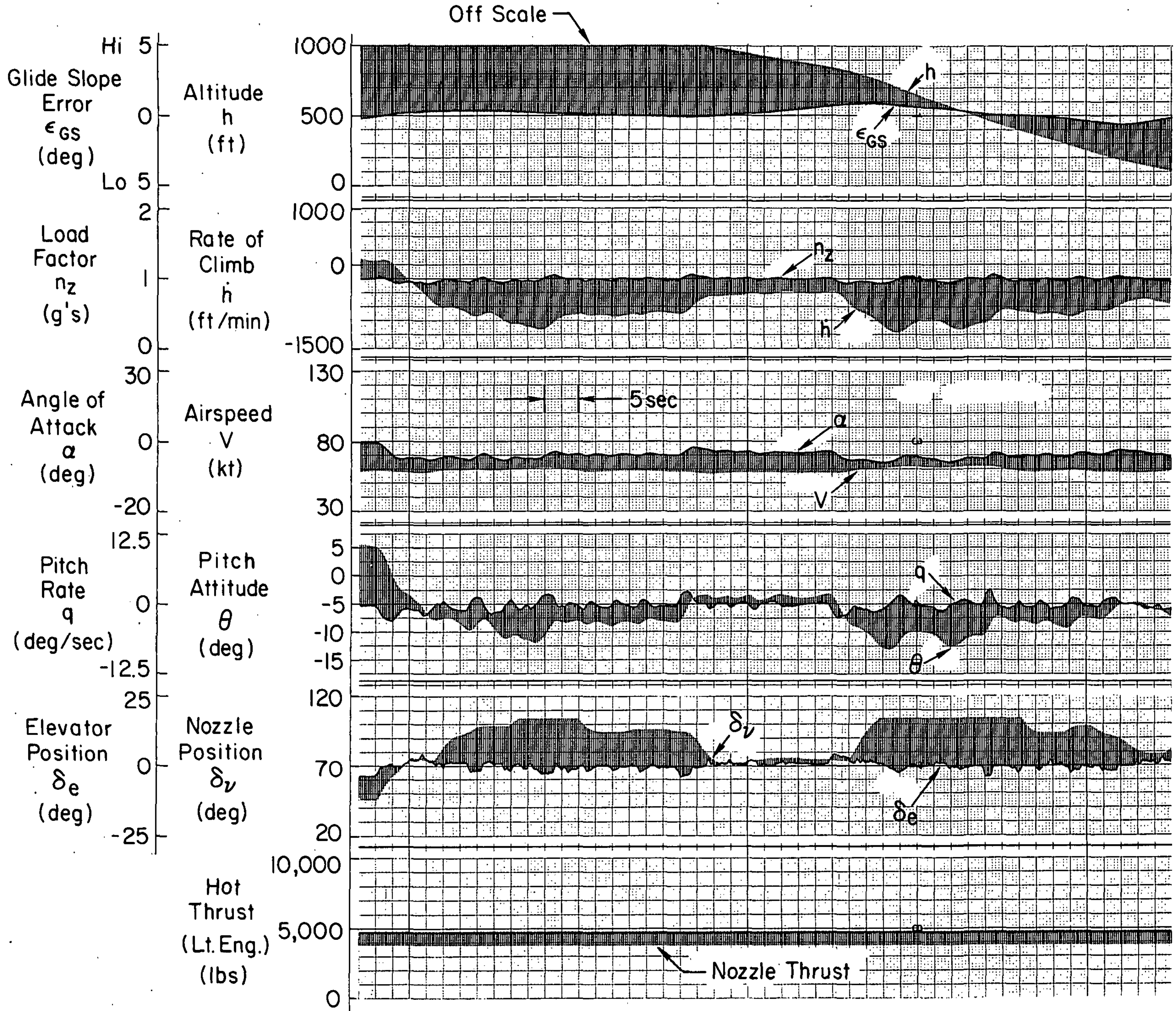


Figure 19. Automatic Mode, No SAS, Turbulence and Shear, Glide Slope Control with Attitude (θ), Pilot B

decelerating, stop, accelerating maneuvers are accomplished quite smoothly at almost constant attitude and angle of attack, as indicated. Notice that the minimum speed is slightly below a commanded speed of 60 kt, but that the error is apparently smaller than indicated by the previously discussed linear analysis.

Figure 21 is a more complete example of the automatic mode operation in that it also includes glide slope acquisition and tracking (however, all in still air). In this case, the decelerate, stop, accelerate, etc., maneuver is very smoothly performed and essentially at constant nozzle thrust. Glide slope acquisition and subsequent tracking are both very smooth and steady.

Figure 22 illustrates the performance attained in the automatic mode with turbulence and shear disturbances. The small perturbations in α and airspeed are notable as is the rapidity and precision of the transition maneuver.

Summary comments on the automatic mode are as follows:

- The pilots liked the vehicle when it flew "like an airplane."
- The V_c bug should be on the IAS meter (rather than on a separate meter — an expedience dictated by lack of a controllable bug on the IAS meter).
- Pilot A said the speed command mode reduced the workload considerably. But he would rather not have a slewing switch on V_c.
- He liked the idea of speed changing a little when he changed γ by moderate amounts. (This was with a gain of 5 deg/kt instead of 10 on the speed error signal.)
- Pilot A liked the automatic mode very much because it gave him good γ control on glide slope with either throttle or attitude. He said "it flies like a real stable airplane."
- Pilot B things the speed command system is tremendous.

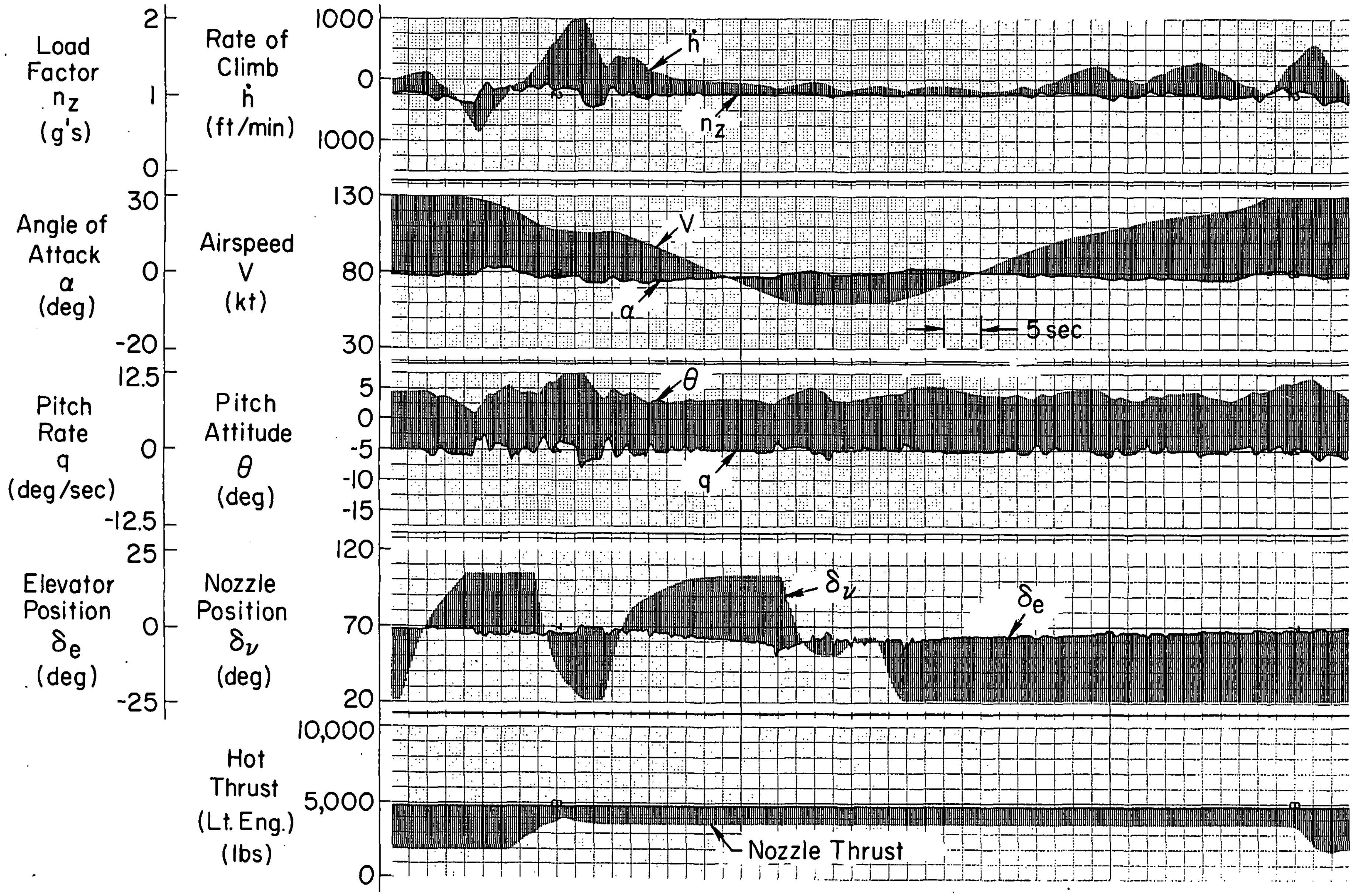


Figure 20. Automatic Mode, Turbulence, Level Flight Decelerate/Stop/Accelerate, Pilot A

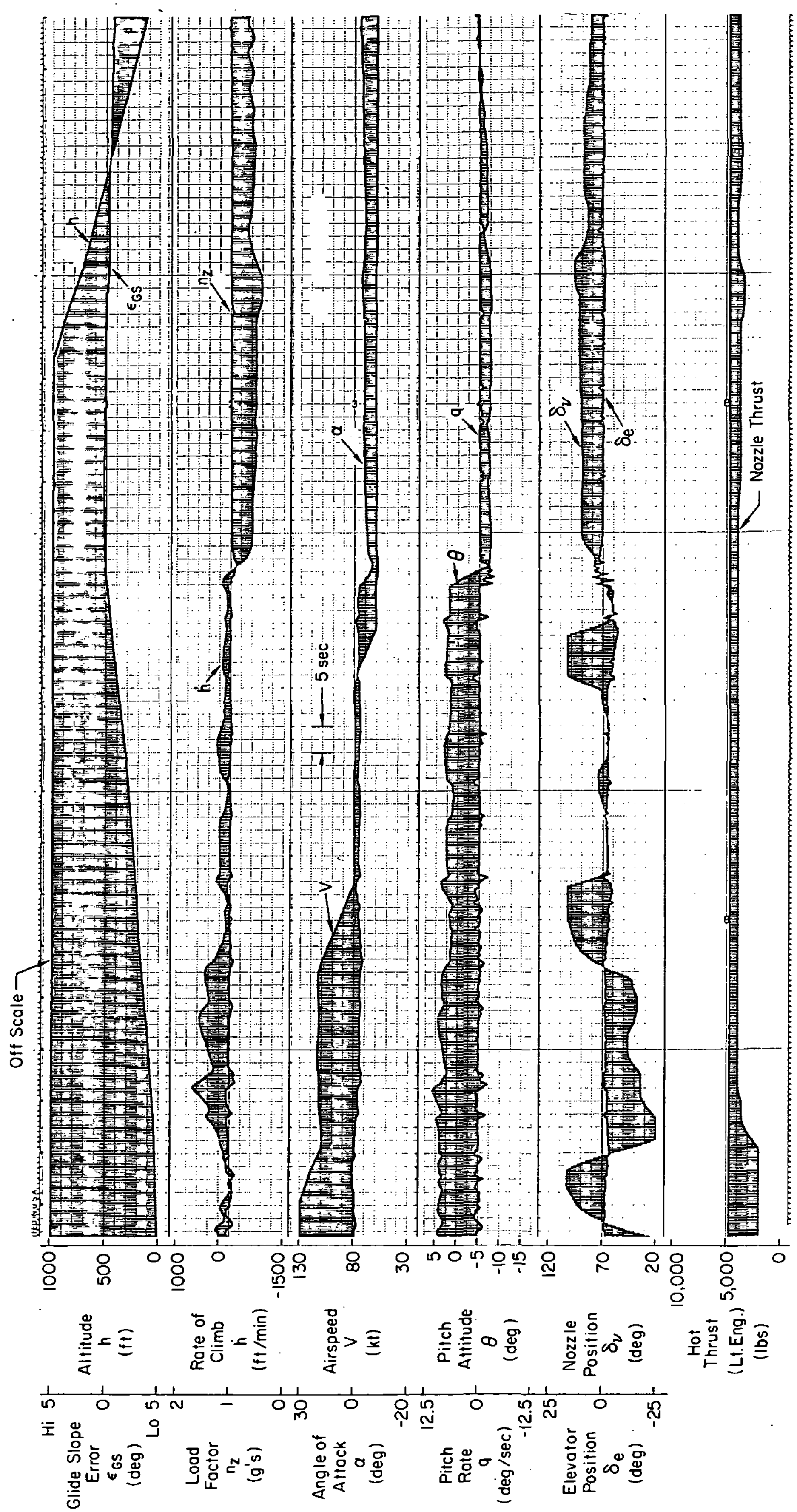


Figure 21. Automatic Mode, Still Air, Stair Step Transition to Glide Slope, Pilot A

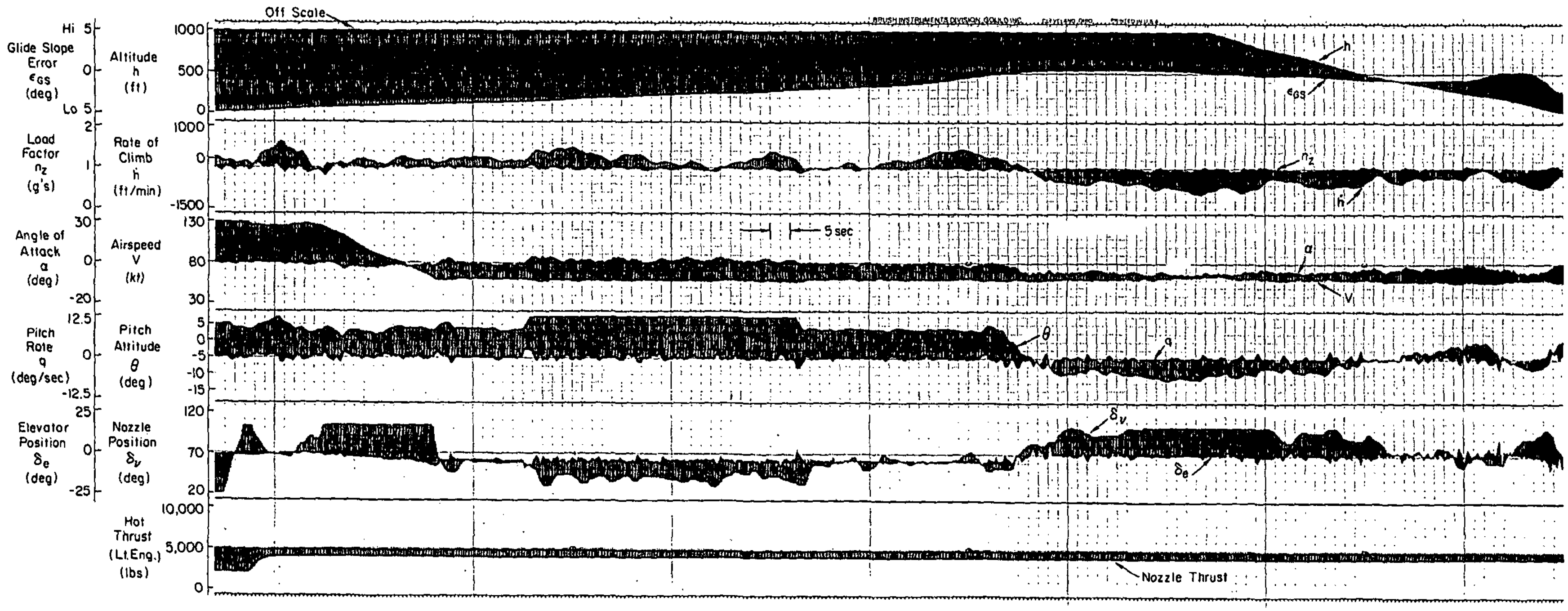


Figure 22. Automatic Mode, Turbulence and Shear, Pilot B

SECTION V

CONCLUSIONS

The basic conclusions, supported by both analysis and simulation, are:

- A four-control (δ_e, δ_F, δ_V, δ_T) manual situation results in excessive pilot workload.

- The concept of using control crossfeeds to constrain the possible vehicle configurations (as well as to simplify the piloting task) was confirmed as useful and desirable. It is especially effective when used also to eliminate relatively unsafe configurations and improve operational performance (e.g., it is noted that throughout the transition there are adequate margins in angle of attack, throttle, and nozzle available for maneuvering the aircraft should the need arise).

- The automatic system was validated as being very desirable. It made the vehicle "fly like an airplane," and made it easy to control flight path with either attitude or throttle.

Additional, incidental findings specific to the Augmentor Wing aircraft configuration are listed below.

- For standardization, the cockpit controls should be moved down to the center console.

- Acceleration/deceleration should be accomplished via the nozzle during transition.

- When nozzle is crossfed from flap, then the nozzle indicator gauge should be part of the flap gauge so that the pilot can tell at a glance what the appropriate trim nozzle position should be.

- For the automatic system, the commanded speed should be displayed on the IAS meter.

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